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XXVIII COURSE

Fuel Cell Systems for Marine Applications

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TESI DI DOTTORATO

DOTTORATO DI RICERCA IN INGFEGNERIA DELLE MACCHINE E DEI SISTEMI
PER L'ENERGIA, L'AMBIENTE E I TRASPORTI
CICLO XXVIII

Sistemi alimentati a idrogeno per applicazioni navali

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Fuel Cell Systems for Marine Applications

Abstract

The aim of this work is the assessment of the most suitable hydrogen solution for ship applications and the definition of the role of hydrogen as alternative fuel for shipping. The importance of the "Hydrogen Technologies" for ships comes from the most important social challenge that is driving innovation in the shipping sector: Environmental Challenge.

The PhD research project encountered important development both from the industrial and the academic side that brought to the construction of a joint laboratory between Fincantieri and the Polytechnic School of the University of Genoa, the: HI-SEA laboratory, dedicated to the study of fuel cell system for marine application. Moreover the simulation modelling and experimental results developed during the PhD research on the PEM fuel cell and MH hydrogen storage systems, found an application in the nautical sector. The former brought to a patent and the creation of a dedicated start-up company named H2Boat, that was recognised as University spin-off.

The first part of the study define the role of hydrogen as alternative energy vector (fuel) for marine application, analysing the complex context in which it is supposed to be used. In part 2.1 a detailed assessment of the characteristics of different alternative fuels have been conducted. The complexity of work brought to the construction of comparative models, descripted in part 2.2 that have been used to analyse the characteristic of various alternative solution. An analysis of the PEM FCS state of the art is presented in part 2.3 together with the definition of FCS design for marine application in part 2.4.

The study of the hydrogen technologies considered also the definition of simulation models of fuel cell systems and metal hydride hydrogen storage system 3.2. The former has also been assessed towards experimental tests, presented in part 3.3. The models have been used to develop larger laboratory, to define correct operative parameters and FCS design.

Finally a number of application developed during the PhD study are proposed in part 4 to show the goal of the research that is still under development.

Acknowledgments

A Freddie.

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Nomenclature

AC	Alternate Current
ADC	Analogic Ditital Conversion
AFC	Alkaline Fuel Cell
ALS	All Electric Ship
ATR	Autothermal Reformer
AUX	Auxiliaries
BAT	Batteries
BoP	Balance of Plant
CCH2	Cryo-Compressed Hydrogen Storage
CH2	Compressed Hydrogen
CO2	Carbod Dioxide
CO2e	Equivalent Carbon Dioxide
DAQ	Data Acquisition System
DC	Direct Current
DF	Dual Fuel
DMA	Distillate Marine Oil grade A
DMB	Distillate Marine Oil grade B
ECA	Emission Controlled Area
EPA	United States Environmental Protection Agency
ETA	Efficiency
EU	European Union
FC	Fuel Cell
FCS	Fuel Cell System
FO	Fuel Oil
GHG	Green House Gasses
GWP	Global Warming Potential
H2	Hydrogen
HTPEM	High Temperature Proton Exchange Membrane
ICE	Internal Combustion Engine
IGC	International Gas Carrier Code (IMO)
IGF	International Code of Safety for Ships using Gases or other Low flashpoint Fuels
IMO	International Marittime Organization
LH2	Liquid Hydrogen
LNG	Liquified Natural Gas
LPG	Liquified Petroleum Gas
LSFO	Low Sulphur Fuel Oil
MARPOL	International Convention for the Prevention of Pollution from Ships (IMO)
MCFC	Molten Carbonate Fuel Cell
MeOH	Methanol
MEPC	Marine Environment Protection Committee
MH	Metal Hydride
MH2	Metal Hydride hydrogen storage
MSC	Maritime Safety Committee (IMO)
NECA	Nitrogen oxide Emission Controlled Area
NG	Natural Gas
NOx	Nitrogen Oxide

NTP	Normal Temperature and Pressure
OEM	Original Equipement Manufacturer
PAFC	Phosphoric Acid Fuel Cell
PEM	Proton Exchange Membrane
PM	Particulate Matter
POX	Partial Oxidation
RMB	Residual Marine Oil grade B
SECA	Sulphur Emission Controlled Area
SOA	State Of the Art
SOFC	Solid Oxide Fuel Cell
SOLAS	Safety Of Life At Sea (IMO)
SOx	Sulphur Oxide
SR	Steam Reformer
SSS	Short Sea Shipping
TG	Gas Turbine
USA	United States of America

1. Introduction and Motivations

The general goal of the PhD research program was the assessment of the potential impact of hydrogen technologies in the shipping industry. For this reason, the use of hydrogen as alternative fuel for ships has been analysed and confronted with other solutions through the benchmark of important design parameters in order to find the most suitable solution, in terms of ship and power system design, able to exploit the hydrogen technologies advantages towards a future low emission ship design.

Virtually, all kind of ships can be powered by fuel cells fuelled with pure hydrogen produced from renewable sources, eliminating any source of pollutants from ships. On the contrary, from an economic point of view, hydrogen technologies cannot be installed on-board any kind of ships, because are too costly. Where is the right balance between technical and economical aspects for hydrogen application on-board ships? Is hydrogen a real alternative solution for ships and shipping?

All ships are a good target for the future application of low emission power systems, hydrogen and the related technologies are among the most promising solutions but, in order to exploit their potential, a comprehensive evaluation of their performance and of ship applications must be done. Not only in comparison with other alternative fuels or power system solutions, but also against other innovations not directly connected to power generation, as well as to the future context in which they will be installed. Challenging solutions should be adopted also to pursue the natural increasing use of electricity on-board and to better comply with rule requirements on safety and emission reduction.

Only throughout the “big picture”, it will be possible to define the power system specifications able to comply with both technical and economical requirements that will permit the development of this technology for marine application.

Even if the assessment of the use of alternative fuel in shipping was limited to hydrogen, a significant analysis is difficult due to the complex interaction between technical and economic aspects. It is possible to observe this complexity from the available literature on the topic, starting from the authors. The use of hydrogen as marine fuel involve National and International, Public and Private entities, not only of the marine sector but also from land based sectors as energy, health, transport and others. The work of Carlo Raucci at all. (1) (2) is a good example to understand the complexity of the ***“big picture”***, focused in the hydrogen applications. The overall evaluation of the carbon dioxide reducing technologies for example, as the one proposed by J. Calleya (3), is an even more complex exercise whose importance is given by the efforts spent by IMO itself to produce similar studies (4).

The former gives important information on the main drivers and barriers to the implementation of emission controls and energy efficiency measures, evaluated towards a survey conducted among port area stakeholder category: port authorities and terminals, ship owners and operators, equipment manufacturers as well as governmental and regulatory authorities.

Indeed the study will raise the importance of ***port areas*** with respect to the environmental impact of shipping and the main drivers, to the implementations of energy efficiency measures, among which, hydrogen technologies belongs.

1.1 Drivers and Barriers

Before to introduce the role of hydrogen, it is important to understand what are the main drivers to the implementation of innovative fuels and technologies.

The whole study, as many others, is based on the International Maritime Organization (IMO) fundamental:

"Concept of a Sustainable Maritime Transportation System"

The concept takes birth after the United Nation (UN) Conference on Sustainable Development held in Rio de Janeiro in 2012, known as Rio+20, to working towards a transition to a "green economy" (5). IMO has developed the concept of a Sustainable Maritime Transportation System (6), which includes a set of goals and actions, to highlight the importance of maritime transportation by focusing among other, on: Energy efficiency and ship-port interface, Energy supply for ships and new technology and innovations.

The concept point out the importance of a set of drivers that can be grouped into the ***Environmental Challenge drivers***. These drivers alone are not able to compel a main change. Other drivers have to be considered too, such as political and economic aspects.

Environmental Challenge drivers:

- Air pollutants;
- GHG/CO2;
- Water pollution;
- Noise;
- Biodiversity.

Political drivers:

- Community and Public pressure;
- Local and Regional Regulation;
- National and Supranational legislation;
- Corporate Social Responsibility.

Economical drivers:

- Fuel price and availability;
- Technology development;
- Operational costs;
- Carbon tax;
- Investment costs.

Several barriers that prevent the introduction of innovative fuels and technologies exist. The barriers are perceived differently by the different stakeholder groups, but can be collected together. For the purpose of the study, the following barriers are considered important:

- Lack of business case;

- Lack of drivers;
- Regulatory constraints;
- Age of ships;
- Only for new ships;
- Only for mechanical propulsion (rules).

In order to evaluate the influence of drivers and barriers, dedicated studies are required, with the involvement of the stakeholder opinions: ship builders, ship owners and operators, equipment manufacturers, port authorities and terminals as well as governmental and regulatory authorities, are among the more important. A good set of information are given by the IMO Report on the emission control and energy efficiency (4), collected towards a survey among the main port area stakeholders.

The results are focused on part of the interested stakeholders, moreover the considered drivers are different from the ones previously listed, but gave anyhow interesting hints on their perception.

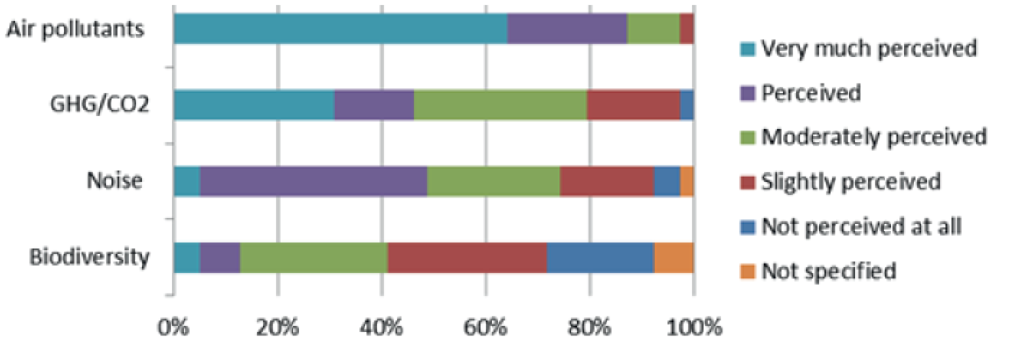

Figure 1. Environmental Challenges perceived by Ports

Figure 1 is an important example of the Environmental Challenge perceived by Ports. An interesting result of this analysis is the relative importance of Air Pollutants with respect to Noise that is generally considered a major environmental challenge for the port community. This result enhance the importance of the reduction of emissions from ships. Figure 2 shows the relative importance of some of the other drivers that play a role in reducing emissions at the ship-port interface.

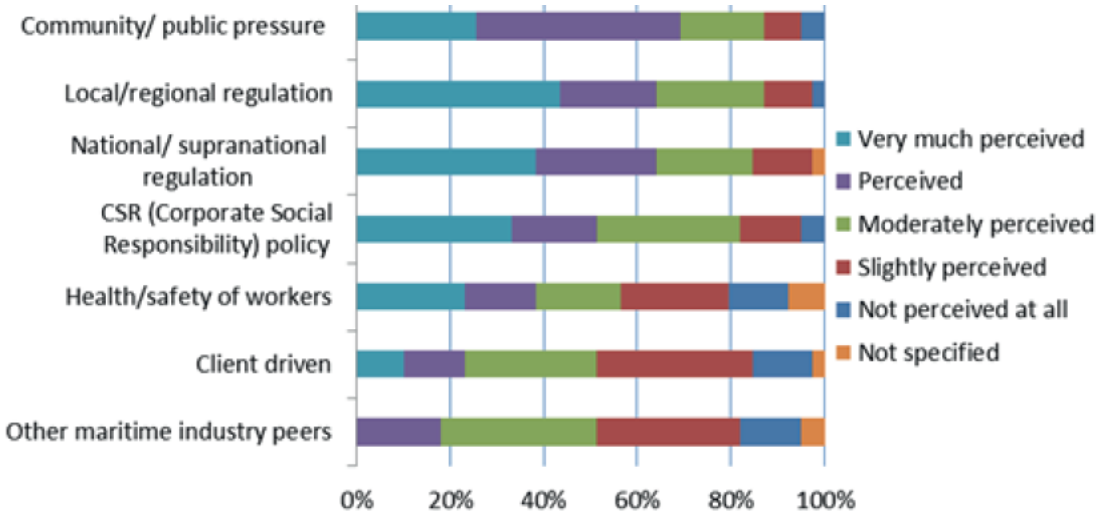

Figure 2. Relative importance of drivers

Finally, the results of the survey on the importance of specific implementation barriers according to responding ship owners is presented from the IMO Report (4). Figure 3 shows important aspects that are often under-estimated in the scientific and academic environment but that are nonetheless important to define key aspects of the technical power systems and ship design as well.

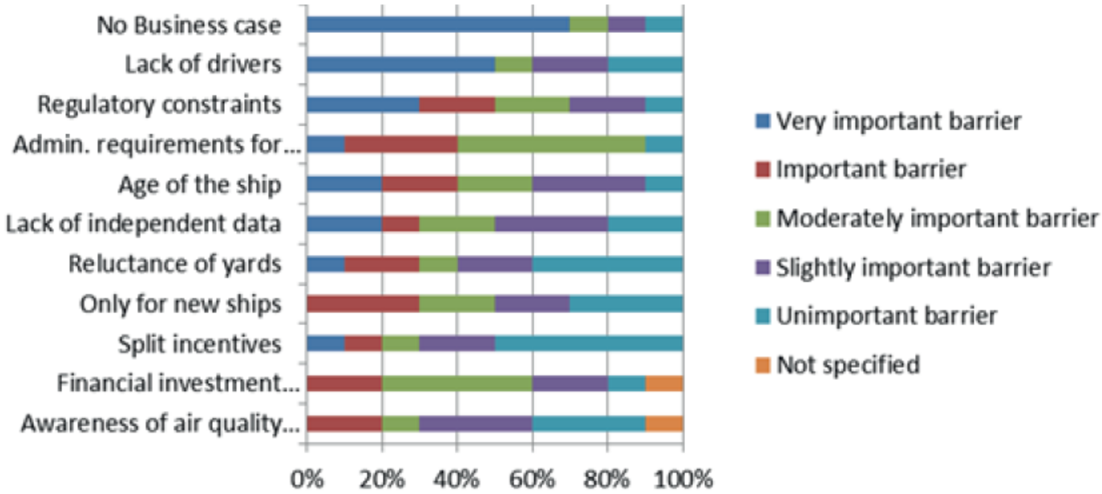

Figure 3.Importance of specific implementation barriers according to responding ship owners

Due to limited resources, it was not possible to collect similar data during the period of the study, but important information have been collected during various projects for the application of hydrogen technologies onboard Mega Yacht, Cruise Passenger Ships and Ferries (Chapter 4), that brought to the construction of important professional experience. Together with the aforementioned data, the global picture that can be extracted confirm the main results of Figure 1, Figure 2 and Figure 3. Among the considered barriers, it is interesting to observe the importance that has been given to Business Cases, Regulatory Constraints, Age of the ships and Lack of independent data. All of them have been encountered during the cited project experiences.

While Business Cases are related to market aspects more than on technical aspects, Regulatory Constraints are related to the rule framework principally established by the IMO and Classification Societies. The introduction of new rules for the adoption of innovative technologies on-board are fundamental since they can result as a barrier or a driver depending on many factors, among which the ***knowledge on the innovative technologies*** is the most important. For hydrogen, this aspect result to be a major obstacle due to the shortage of its applications. Age of ships and Lack of independent data are other aspects that match the maturated experience, the influence of which will be better described in the following.

Another important conclusion that is possible to draw from the driver analysis is the relative importance of Air pollutants and GHG/CO2 among the Environmental Challenges drivers. The reason comes from the IMO fundamental concept, which is supported by the international movement towards a transition to a "green economy", whose main result is the increase of the community consciousness about the environmental challenge. The most noticeable and discussed aspect of shipping pollution is air pollution. It is possible to state that the survey results reflect this global trend, confirming the public pressure as one of the most important drivers.

Public opinion though, partially collide into the real numbers of shipping emissions. The Third IMO greenhouse gas study estimates that for the period 2007-2012, on average, shipping accounted for approximately 2.8% of annual global CO2e (3.1% CO2) and the study's scenarios project an increase of 50-250% in the period up to 2015 (7). Other sectors like Electricity and Heat production and

Agriculture are responsible of 25% and 24% respectively of global GHGs emission (8), a huge difference from the 2.8% of shipping. The IPCC Fifth Assessment Report (AR5) states that the global NOx and SOx emission from all shipping represent about 15% and 13% respectively of the whole anthropogenic sources (8).

On the contrary, ships move about 90% of cargo and commodities all around the world, with more than 70% ton-km (6) (9). It can be stated that “Maritime transport is the backbone of world trade and Globalization” (6).

For this reason, it is considered the most efficient transport method in terms of energy efficiency and the most important one for the trade sector. These numbers are the reasons why emissions controls and efficiency measures which applications have been introduced only lately. In spite of that, IMO introduced a series of measure to reduce ship emissions together with the most developed countries administrations, EU and USA.

Air pollution from ships is generated by diesel engines that burn fuel oil, HFO in general with a high content of sulfur, producing sulfur dioxide, nitrogen oxide and particulate, in addition to carbon monoxide, carbon dioxide, and hydrocarbons. Diesel exhaust has been classified by EPA as a likely human carcinogen. EPA recognizes that emissions from marine diesel engines contribute to ozone as well as adverse health effects associated with ambient concentrations of particulate matter and visibility, haze, acid deposition, and eutrophication and nitrification of water (10).

The study considered the most important emissions regulated by IMO and EU regulations:

- SOx;
- NOx;
- PM;
- CO2.

Table 1 shows the most important measure in terms of air emission reduction for ship under operation and new construction, produced by IMO and EU. Alternative fuels have been considered as alternative solution to the reduction of SOx due to the difficulties in exhaust treatment of ICEs and to the combined high price and low production rate of LSFO.

<table>
<tr><th></th><th></th><th colspan="2">SOx</th><th colspan="2">NOx</th><th>CO2</th><th colspan="2">ETA</th></tr>
<tr><td></td><td>Main cause</td><td colspan="2">Sulphur content in fuel</td><td colspan="2">Temperature of formation</td><td>Fuel Consumption</td><td colspan="2">Operation, Technology</td></tr>
<tr><td rowspan="2">Ship in operation</td><td>EU Regulations</td><td colspan="2">DIRECTIVE 2012/33/EU
EU active</td><td colspan="2">EU AIR QUALITY 2008/50/EU*
EU active</td><td>EU MVR 2009/16/EC
EU active</td><td colspan="2"></td></tr>
<tr><td>IMO Regulations</td><td colspan="2">MARPOL Amendment
SECA zone
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NECA zone
USA tier III | EU tier II**</td><td>MARPOL Amendment
DCS
Worldwide</td><td colspan="2">MARPOL Amendment
SEEMP
Worldwide</td></tr>
<tr><td rowspan="2">Alternative fuels</td><td>EU Regulations</td><td colspan="2">DIRECTIVE 2014/94/EU
EU active</td><td rowspan="2">New ship</td><td></td><td></td><td rowspan="2">New ship</td><td></td></tr>
<tr><td>IMO Regulations</td><td colspan="2">SOLAS Amendment
IGF code
Worldwide</td><td>SOLAS Amendment
NECA tier III
Worldwide</td><td></td><td>MARPOL Amendment
EEDI
Worldwide</td></tr>
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*objectives only
* tier III from 2021

Table 1. IMO and EU measure to control ship emissions

A deeper analysis of the regulations for the control of ship emissions will be given during the context assessment. It is possible to remark the different application of NOx limits between USA and EU inside NECA areas from IMO, due to the complex fulfillment of tier III limits and the consequent contrast from ship operators and the National entities they belongs. A clear illustration of why ship owners are reluctant to be early adopters of new technologies.

Another important remark concern the GHG/CO2 emissions. Up to now, no measure has been taken to reduce the GHG/CO2 emission from ships, also because it is directly connected to the fuel consumption and cannot be reduced as sulfur from fuel oil, but only by changing fuel or reducing fuel consumption enhancing ship efficiency. The adopted measures that are under the introduction phase, aim to evaluate the CO2 production of ships from fuel consumption in order to help the introduction of a future tax over CO2 emissions. The former would represent the main driver to the shift from fuel oil to alternative fuels with reduced carbon dioxide factors like hydrogen, as demonstrated by the TIAM-UCL and GloTraM models by Raucci at all. (2).

Indeed political choices will strongly influence the large introduction of hydrogen technologies on ships, although regulation actually represent the main driver to its introduction. Once the rule framework will be in place, the technical-economic analysis, some of which are presented in Chapter 4, will define the most suitable hydrogen application on-board ships.

1.2 Hydrogen as alternative fuel

"Alternative Fuels" means fuels or power sources which serve, at least partly, as a substitute for fossil oil sources in the energy supply to ***transport*** and which have the potential to contribute to its decarbonisation and enhance the environmental performance of the transport sector, as established by EU Directive 2014/94.

The requirements of the Directive on ***sulphur content*** in marine fuels (2012/33/EU) are the main drivers to the use of alternative fuels, as part of a broadly European strategy. The EU institutions are promoting the use of alternative fuels also to reduce the countries dependence from imported oil. The EU imports 53% of all the energy it consumes, at a cost of more than €1 billion per day. Energy also makes up more than 20% of total EU imports (11). Specifically, the EU imports:

- 90% of its crude oil;
- 66% of its natural gas;
- 42% of its coal and other solid fuels;
- 40% of its uranium and other nuclear fuels.

Moreover, The European Council adopted in 2007 ambitious energy and climate change objectives for 2020 – to reduce greenhouse gas emissions by 20%, rising to 30% if the conditions are right, to increase the share of renewable energy to 20% and to make a 20% improvement in energy efficiency. The European Council has also given a long term commitment to the decarbonisation path with a target for the EU and other industrialised countries of 80 to 95% cuts in emissions by 2050 (12).

Many different ***alternative fuels*** can be used in shipping. The most commonly considered today is Liquefied Natural Gas (LNG), but many other are already present in niche market or are potentially ready to be used on-board ships. In the following a list of the principal alternative fuels considered for ships:

- Biodiesel;

- Methanol;
- Liquefied Natural Gas (LNG);
- Liquefied Petroleum Gas (LPG);
- Ethanol and Dimethyl Ether (DME);
- Biogas;
- Nuclear fuel;
- Hydrogen;
- Electricity.

Electricity and hydrogen are different from other energy sources because they are secondary sources of energy. Secondary sources of energy—energy carriers—are used to store, move, and deliver energy in an easily useable form. A primary energy source must be used to make secondary sources of energy such as electricity and hydrogen (13).

The main characteristic searched in alternative fuels is the absence of sulphur, a requirement needed to comply with sulphur content regulations. In general, all of them can be used either in combination with conventional, oil-based marine fuels or to completely replace conventional fuels. The fuel properties have to be evaluated together with the energy converter performance to define the efficiency and the emission of other GHG gasses and pollutants such as NOx and Particulate.

In shipping, alternative fuels are considered of high interest, also given the International Maritime Organization prescription for Emission Controlled Areas. Indeed, EU directive is in line with MARPOL Annex VI that require the use of 0.5% sulphur content in EU waters (200 nm) by 2020 and the requirement for passenger vessel of maximum 1.5% in all non-ECA EU waters until 2020.

One ***common challenge***, however, posed by the adoption of most alternative fuels are their physico-chemical characteristics, typically with associated low flashpoints, higher volatilities, different energy content per unit mass and, in some cases, even toxicity. The adoption and entry into force of the draft International Code of Safety for Ships using Gases or other Low flashpoint Fuels (IGF Code), along with proposed amendments to make the Code mandatory under SOLAS, by MSC95, on 11 June 2015, was a decisive step forward in addressing those challenges, at the regulatory level (14).

The IGF Code includes mandatory provisions for the arrangement, installation, control and monitoring of machinery, equipment and systems using low flashpoint fuels, such as liquefied natural gas (LNG), to minimize the risk to the ship, its crew and the environment, having regard to the nature of the fuels involved. LNG has been the first focus of the IGF Code; however provisions for Methyl/Ethyl alcohols, Fuels Cells and Low Flashpoint Oil Fuels are being drafted for the expected first revision of the code, in 2020/21. Hydrogen is still missing in the IMO groups discussion, for this reason its use on-board will rely on ***alternative design*** options that even if comply with the SOLAS, require to be accepted by each singular flag administration of the countries where the ships has to be deployed, resulting in a major obstacle to its introduction and use as alternative fuel.

To be effective, alternative fuels need to be introduced into the market together with appropriate infrastructures and adequate technological and commercial innovation in the field of power generation and fuel/energy storage. Important studies (15) (16) describe the importance of the refuelling infrastructure for the development of any alternative fuel in the maritime sector.

The peculiarity of Hydrogen comes from its absence in nature (free state) that requires its production either by fossil fuel or by renewable sources by mean of water electrolyser. The author believes that hydrogen technology cannot be defines as such if hydrogen produced by fossil fuel is considered because the most important characteristic of this fuel cease to be present, that is carbon dioxide production.

1.3 Design revolution

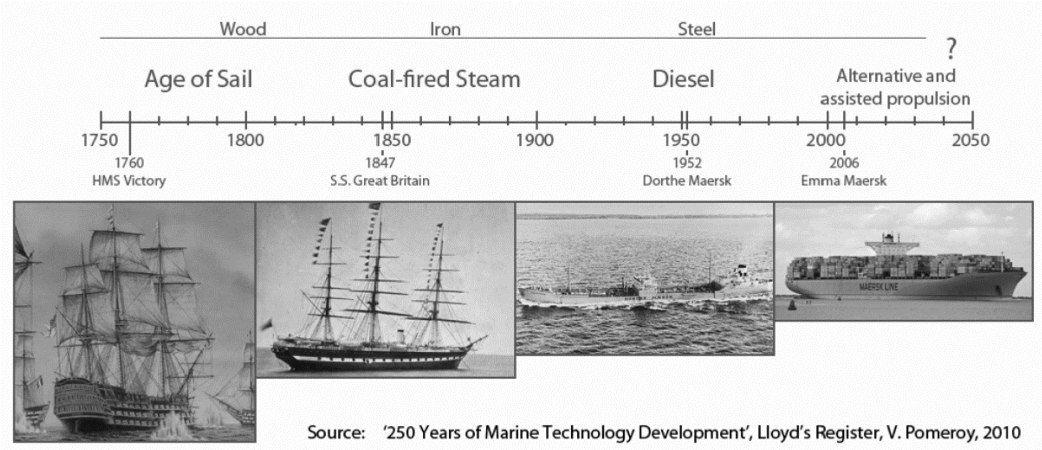


Figure 4. Marine Technology Development

The use of alternative fuel on-board ships will require important design changes, especially inside the machinery room where power production units are installed. But also the traditional centralized machinery room could be affected by the introduction of new technologies, as showed by major changes that already happened in the past of ship design history. That brings to a fundamental concept:

"The introduction of hydrogen in ships will require a global rethink of the ship design"

The first fuel cell in history was officially invented by Sir William Robert Groove, when in 1842 penned a brief note to chemist and physicist Michael Faraday at the Royal Institution, soon after being appointed professor of experimental philosophy at the London Institution. But Groove's first experiments results started to become popular in 1838 towards a lecture in which he described "an ***economical battery*** of Mr Grove's invention, made of alternate plates of iron and thin wood, such as that used by hatters". Shortly after Grove announced his invention, the German-born engineer Moritz Hermann von Jacobi used a bank of Grove's batteries to power an electromagnetic motor boat on the river Neva in Saint Petersburg (17). The 28-foot electric motor boat powered by fuel cells, carrying 14 person at the speed of three miles per hour becomes the first application of a fuel cell, on-board a boat, with an electric motor, a omen to the future!

The first real internal combustion engine though, was invented by Eugenio Basanti and Felice Matteucci in1853, while only in 1892 Rudolf Diesel invented the diesel engine, of which he proved the performance during 1900 world fair, using peanut oil fuel (biodiesel, another omen?).

After this precocious begin, the true history of energy and the culture that depends on that energy, over the past 150 years or so has been rather different. It was coal and oil, rather than hydrogen that powered the 19th and 20th-century economies.

Table 2 resumes roughly some of the ***major changes*** that took place in the ship design and construction during the same period. It is interesting to observe how important changes in the energy source and power generation were connected to the ship design, ship operational profile, built material, political scenario and others (18).

Period	Energy Source	Power Unit	Hull Material	Trade Range	Other
up to 1850	Wind	Sail	Wood	Regional	
up to 1950	Coal	Steam Engine	Iron	Ocean Travels	Riveted
up to today	Oil	Internal Combustion Engines	Steel	Worldwide	Welded

Table 2. Rough table of shipping important changes

During the beginning of the 19th century, sailing ships were shipping all over the world. By late 1840s sailing ships reached their culmination of ship design (Figure 5. The clipper Flying Cloud) when the steam engine appear. During the early days of steamship in late 18th, due to the poor performances of the steam engines, sailing ships maintained a central role in the commercial navigation while steamships were firstly developed for inland navigation where speed were less important. Than in 1819, the first paddle ship using steam power crossed the Atlantic, Figure 6.

Figure 5. The clipper Flying Cloud

The use of mechanical power gradually marginalized the importance of wind as energy source and the ship design changed, eliminating tree and sails from the deck and increasing ship dimensions. During the 1860s iron riveted hulls started to become popular and propellers appears.

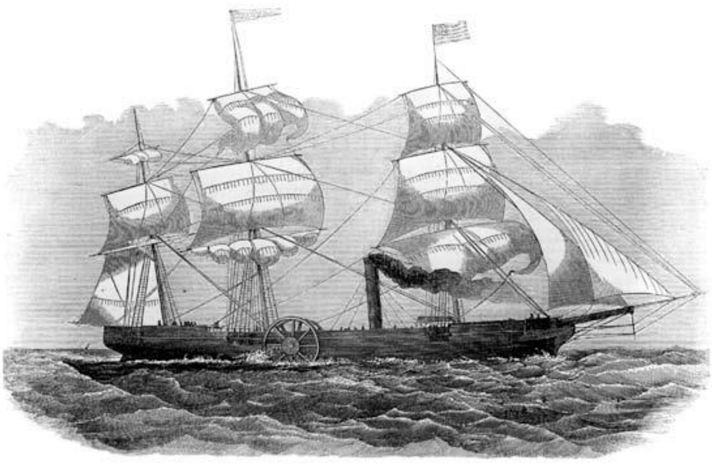


Figure 6. The American paddle ship Savannah, the first ship to use steam power in crossing an ocean

At the beginning of the 20th century, passenger ships became bigger and bigger in order to fulfil the demand of ship operators that were facing the large migration from Europe to USA, Figure 7. Ship design changed again and power systems were based only on mechanical power. Large volumes were dedicated to the storage of coal and human operators were required to run the boilers.

From the early 19th century until the third quarter of the 20th century, steamships crossed the seven seas, gradually eliminating sailing ships from commercial shipping. In the second half of the 20th century, motor ship started to dominate. Twenty years later the invention of the diesel engine, the first four-stroke marine diesel engine ships were operational. Around 1930, two-stroke designs took a strong lead as ships became larger and faster. Between World War I and World War II, the share of marine engine-driven ships increased to approximately 25 percent of the overall ocean-going fleet tonnage. A series of innovations of the diesel engine followed, which made it possible to use heavy fuel oil by mid-1950s, thanks to the introduction of high alkalinity cylinder lubricants required to neutralize the acids generated by the combustion of high sulphur residual fuels. Diesel ships using residual fuel oil gained in popularity and in the second half of the 1960s, motor ships overtook steamships, both in terms of numbers, and in gross tonnage. By the start of the 21st century, motor ships accounted for 98 percent of the world fleet (19). The rise and development of ICEs use in ships occur alongside with ship design major changes.

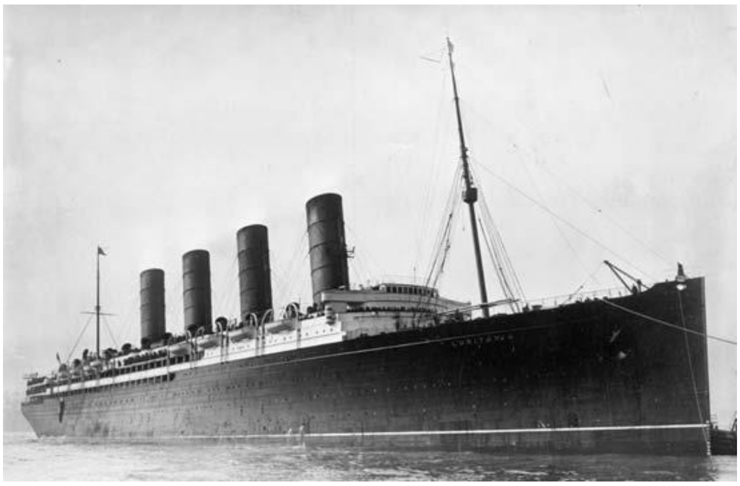


Figure 7. The Cunard ocean liner Lusitania

Important design changes took place inside a time span of 100 years, mainly driven by technology improvements of the propulsion systems, on-board ships that were built to last 20 to 30 years inside a highly conservative environment such as shipping. The speed of markets growth pulled technology development and the introduction of innovative solutions up to now. Even if the global economic growth is slowing down, the total amount of Million tones of goods moved by ships is expected to increase while 90% of cargoes and commodities to all corners of the world are already moved by ships. New technologies are under development at speeds that were unthinkable during the last century. The combination of these factors forecast important changes in the future to come.

Introduction of hydrogen will produce important changes in the machinery room as well as in the fuel storage tanks. From the past, it is possible to observe that new technologies were introduced gradually, starting from local shipping as internal water to be later applied to the whole shipping in the case of improvements. The same path could apply to hydrogen technologies.

More in general, in the case of alternative fuels, for the first time in history new technologies will be pulled by a different driver than the economic/market ones: Environmental challenge. For the first time new technologies with reduced economic performance will be introduced, for this reason it is likely that they will require more time to enter into force.

In order to enhance the performance of future ships, ship design will have to change to better comply with the characteristics of the alternative fuels and related technologies. Moreover, to facilitate the introduction of hydrogen technologies, other future innovations have to be considered:

- Information Communication Technologies (ICT)
- Increased electric consumption
- Distributed generation
- Co-generation and Tri-generation
- Modularity
- Fuel flexibility
- Market changes

The previous list is only a short example of what is considered relevant from the author. Many other innovations are under development and will be probably adopted during the next decades. The original concept thought, can be resumed in the necessity to study and implement the introduction of hydrogen technologies into a future ship. This will require the modification of the ship design to comply with the requirements not only of hydrogen and fuel cells but also with other important future ship innovations. In the following a short list of observation regarding the introduction of hydrogen technology in shipping is reported as cause for reflection:

- Fuel cell are studied separately from hydrogen storage systems, the compatibility of them within the ship architecture will represent the real challenge to marine architectures and engineers;
- Still the concept of higher efficiency with larger ICE run at MCR dim the potential of fuel cells that on the contrary present higher efficiency at partial load;
- Fuel cell modularity will match with ship builders design and construction procedures;
- Ships characterized by higher design complexity will probably be the first platform in which new technologies as fuel cells will be introduced, due to the higher production costs and the fact that the most important shipyards of these kinds of ships are still in EU where the IMO rules are supported by state administration rules.

Other kinds of ships could be affected by the introduction of fuel cells and alternative fuels, in particular pollutants and GHG emissions analysis should drive the choice of the most effective solution and ship typology to aim. But these aspects strongly rely on political and economical decisions that are to be made.

Fuel cell will be used with hydrogen or reformed hydrogen rich syngas to power dedicated ship Auxiliary Systems (as Auxiliary Power Unit AUX), pushed by the main driver, public pressure for environmental changes. These first applications will be mainly considered as public image instruments by ship operators, but will also provide important knowledge in the use of hydrogen technologies. Alongside AUX ships applications, fuel cell will be introduced in niche sectors, mainly of internal water boats and ships, especially for ships with fixed routes inside the same national jurisdiction. The last is thought to be by the author the main target to which the Community (EU) should aim to reduce GHG and air pollution near the coasts, the higher dense inhabited place on earth. The target is Short Sea Shipping.

1.4 Performance

An assessment of the performance of hydrogen ships cannot be made without first fix the following basic assumption:

"The combination of fuel oil and internal combustion engines cannot be match in terms of performance (energy and power density) with alternative fuels or batteries"

Even if the ICEs efficiency is limited by the Carnot cycle, recent technology improvements made marine engines OEMs claim 50-52% (20) thermal efficiency. During real working cycles and especially at partial load the engine will work at a reduced efficiency, but nonetheless a value of 40% can be considered high. This fact reduce the potential benefit of fuel cells that usually works with efficiency that can be considered of about 50%. In terms of power density, per weight or per volume, ICEs performance remains very difficult to overrun.

For what concerns the energy density, it depends by the properties of the fuel. Table 7 resume the most important factors of fuels for marine applications, the simple comparison between the numbers easily explain the truthfulness of the basic assumption. Table 7 refers to fuel properties rather than storage system properties, that are even worse for alternative fuels. Two important considerations can be made. First, the performance of a fuel is much more related to its Energy Density (kWh/l) rather that its Specific Energy (kWh/kg). Storage volume will represent the major challenge to the use of alternative fuels, especially hydrogen. Second, a real GHGs reduction can be achieved only using carbon free fuels, fossil fuels, whatever the kind, will always emit CO_2. Moreover, some of that have a high Global Warming Potential (GWP), in particular Methane, the main constituent of LNG have a GWP of 84 over 20-years period.

Alongside the performance in terms of energy and power density, the comparison should also consider the emission factors. In order to be comparable, the same parameters have to be considered, for this reason a short evaluation of the performance in terms of weight and volumes of the exhaust gas treatment system required to reduce NOx and SOx has been made.

The study presents and discusses the use of Comparative Models as instruments for the analysis of technical system specification and the comparison between systems with different characteristics with a statistic method. Moreover the study shows how the Comparative Models have been used as tools to steer the study towards the right conclusions.

1.5 Context

In order to evaluate the opportunity to install fuel cells systems on-board of ships, it is of crucial importance the assessment of the international background about safety and classification procedures for fuel cell ships. The "rule framework" in shipping is defined by the following actors:

- International Maritime Organisation (IMO): Mandatory Conventions and Codes
- International Association of Classification Societies (IACS): Unified Requirements
- Classification Societies: e.g. RINA Rules for Classification and Construction; Guidelines, etc.
- Technical Standards: e.g. ISO, IEC, etc.

IMO is the source of approximately 60 legal instruments that guide the regulatory development of its member states to improve safety at sea, facilitate trade among seafaring states and protect the maritime environment. Among them the most important is The International Convention for the Safety of Life at Sea (SOLAS). Until 2009 the Convention didn't have any provisions for use of gas as fuel on ships other than gas carriers. As a matter of fact, the SOLAS, Part 1, Chapter II-2, Part B, Regulation 4 2.1 established the following limitations in the use of oils as a fuel:

The following limitations apply to the use of oil as fuel:

1. .[. . .] no oil fuel with a ash-point of less than 60 °C shall be used

2. in the emergency generators, oil fuel with a ash-point of not less than 43 °C may be used

Recognizing the need for the development of a code for gas-fuelled ships, IMO started the development of the International Code of Safety for Gas-fuelled Ships (IGF Code) that still is under development. In the meanwhile, the Maritime Safety Committee, noting that the SOLAS 1974 didn't has any provisions on the topic and acknowledging that, provides guidance to the Administrations of the gas-fuelled engine installations in ships that in 2009 was published as “Interim guidelines on safety for natural gas-fuelled engine installation in ships”, Resolution MSC 285(86), adopted from the 1 June 2019.

The new mandatory code for ships fuelled by gases or other low-flashpoint fuels (IGF Code) was adopted by IMO's Maritime Safety Committee (MSC), along with amendments to make the Code mandatory under the International Convention for the Safety of Life at Sea (SOLAS).

The amendments to SOLAS chapter II-1 (Construction – Structure, subdivision and stability, machinery and electrical installations), include amendments to Part F Alternative design and arrangements, to provide a methodology for alternative design and arrangements for machinery, electrical installations and low-flashpoint fuel storage and distribution systems; and a new Part G Ships using low-flashpoint fuels, to add new regulations to require ships constructed after the expected date of entry into force of 1 January 2017 to comply with the requirements of the IGF Code, together with related amendments to chapter II-2 and Appendix (Certificates).

Presently the IGF Code contains mandatory provisions for the arrangement, installation, control and monitoring of machinery, equipment and systems using low-flashpoint fuels, focusing initially on LNG.

The IMO sub-committee on carriage of cargoes and containers (CCC), is developing safety provision for ships using fuel cells, with the preliminary drafting of a proposed new part E on fuel cell power installations to the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code). Part E would cover installation, fire safety and other relevant matters. The IGF Code Correspondence Group is developing draft technical provisions for the safety of ships using methyl/ethyl alcohol as fuel, while hydrogen storage was not considered.

But IMO gives provision also on the air emission limitations, that are the main driver to the introduction of alternative fuels, the IMO Marpol Annex VI.

After an initial focus on water pollution due to shipping activities, and in particular oil transport, in the 1990's the IMO focused on airborne emissions from ships. In 1997 the new Annex VI was added to the MARPOL (International Convention for the Prevention of Pollution from Ships), and in May 2005 it entered into force. Following the improvements in existing technologies, Annex VI was revised by the Marine Environment Protection Committee (MEPC) by tightening emissions limits, and this updated version came into force in July 2010. Furthermore, Emission Control Areas (ECAs), with lower emission limits, were issued. The first ECAs were in the Baltic and North Sea, with lower limits on SOx emissions. Later new ECAs were issued in the US coastal areas and in the Caribbean, and in those areas NOx and particulate matter (PM) have been also taken into account. NOx and SOx emissions, which are of particular interest, are regulated in regulation 13 and 14 of MARPOL Annex VI respectively.

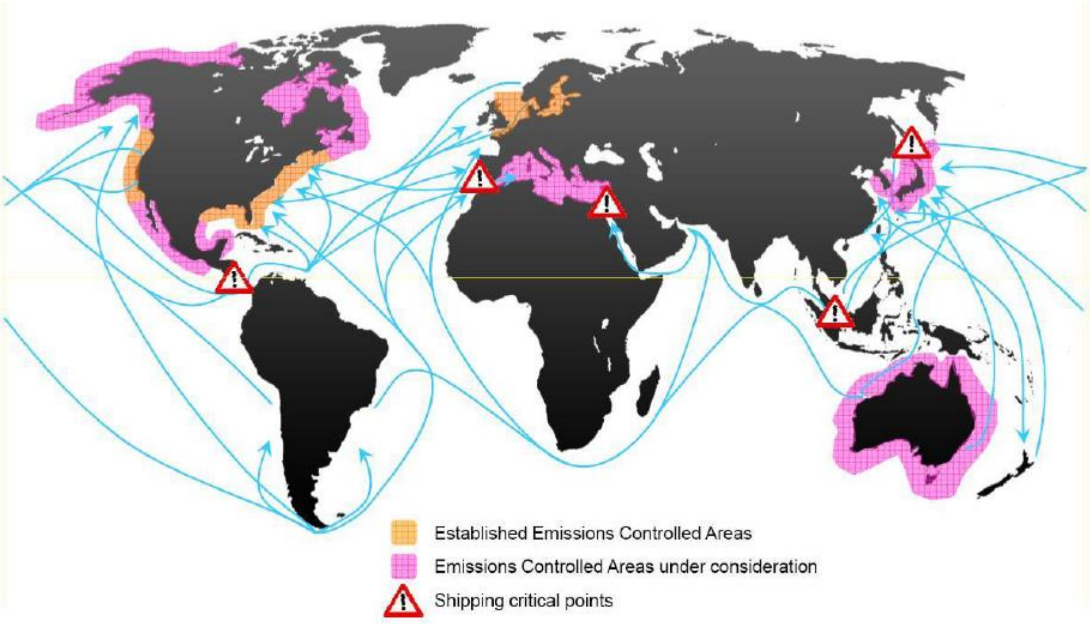


Figure 8. Geographical mapping of the ECAs at 2017

To comply with the MARPOL, every engine with a power > 130 kW installed on a ship built after 1st January 2000 must obtain the Engine International Air Pollution Prevention (EIAPP) Certificate, certifying that the emissions of NOx are lower than established in regulation 13 of MARPOL Annex VI. Each engine is then tested to further verify its compliance.

The NOx emissions limits are divided in three Tiers, depending on the date of built of the ship on which the engine is installed. For each Tier, actual values are dependant on the engine's rated speed. Tier I, whose limits were thought to cause a 30% reduction over those typical in the nineties, were applied to engines installed ship built after 1st January 2000. Tier II and Tier III limits were subsequently introduced.

Tier	Ship construction date after	Total weighted cycle emission limit (g/kWh) n = engine's rated speed (rpm)		
		n < 130	130 < n < 1999	n > 2000
I	1st January 2000	17	$45 * n^{-0.2}$	9.8
II	1st January 2011	14.4	$44 * n^{-0.23}$	7.7
III	1st January 2016 (ECAs)	3.4	$9 * n^{-0.2}$	2.0

Table 3. NOx emission limits

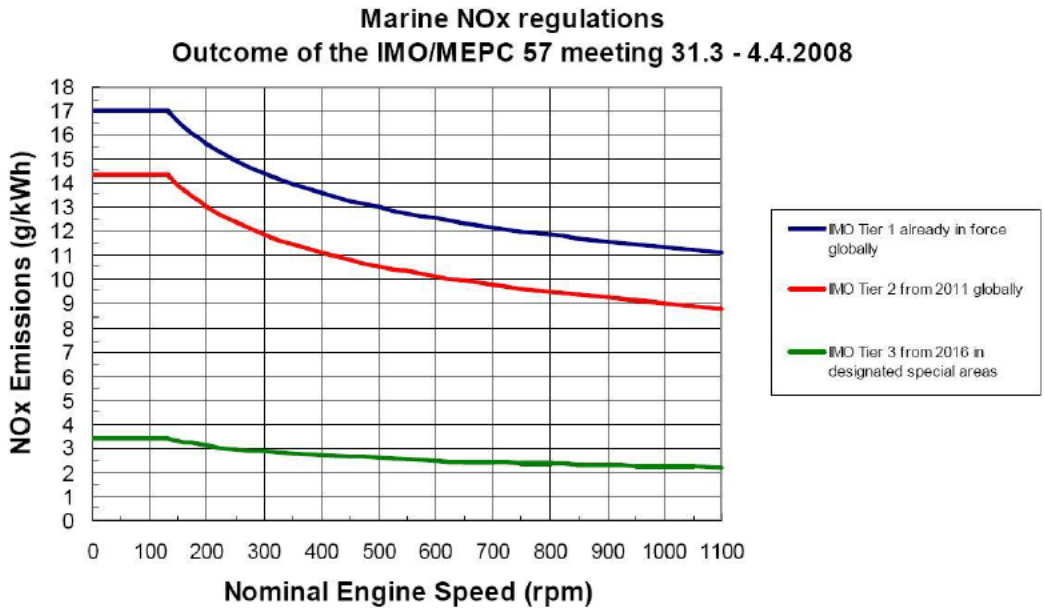


Table 4. Graphical representation of NOx emission limits

While NOx emissions limits are mainly relative to the engines themselves, SOx emissions are related to the fuel used. Therefore, the limits are imposed on the maximum sulphur content of the fuel oils as loaded, bunkered, and subsequently used on board.

As for NOx emissions, these limits have been gradually lowered, and even lower limits have been established in the ECAs. Table 5 is a summary of the past and current limits on SOx emissions, expressed in terms of % m/m (mass).

Outside an ECA established to limit SOx and particulate matter emissions	Inside an ECA established to limit SOx and particulate matter emissions
4.50% m/m prior to 1 January 2012	1.50% m/m prior to 1 July 2010
3.50% m/m on and after 1 January 2012	1.00% m/m on and after 1 July 2010
0.50% m/m on and after 1 January 2020	0.10% m/m on and after 1 January 2015

Table 5. Sulphur limits

The date of entry into force of the lower limit outside ECAs is pending upon studies on the effective availability of the required fuel oil.

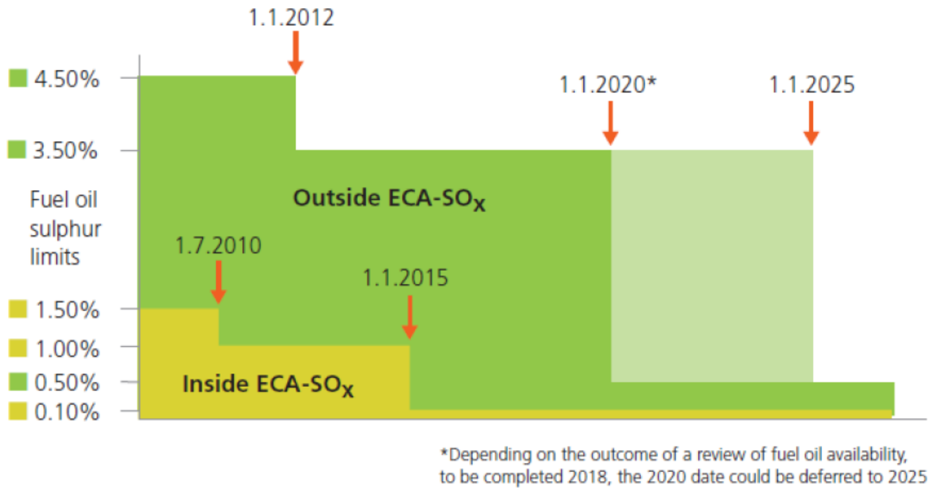


Table 6. Graphical representation of S fuel maximum content

2. Energy vectors analysis and fuel cell technologies comparison

2.1 Alternative energy vectors comparative study

Today, 98% of the world fleet is powered by Internal Combustion Engines (ICEs) fuelled with fuel oil (FO) (19). After the emission limitation that has been imposed by the international community (IMO, EU and USA mainly), the supremacy of the union between Fuel Oil and Internal Combustion Engines has been questioned. The sulphur limitation can be achieved only through the separation of sulphur components either by the fuel or by the exhaust, while nitrogen oxide requirements have to be challenged by the generators, namely ICEs. Moreover a reduction of GHGs from ships is among the community objectives (21). Although any national or international organization has been able to set an object parameter on GHGs reduction, it can only be achieved operating on the fuel characteristic since carbon sequestration from the exhausts, even if possible seems not to be a mature technology, especially for ships.

The goal of the feasibility study on energy vectors for maritime application is to define a panoramic of different fuels or energy vectors available to comply with Sulphur and GHGs requirements. A selection of the main energy vectors for maritime applications has been done starting from literature (15):

- FO (different types);
- LSFO;
- Byo-Diesel;
- LPG;
- Methanol;
- Natural Gas;
- Hydrogen.

The study is composed by an ***assessment of the energy vectors characteristics***, considering all the possible traditional fuels for marine applications and the most promising alternative fuels. To complete the study, a ***comparative analysis between energy vectors*** and more important, the ***comparative analysis of energy vectors storage systems*** has been done.

In order to clarify important aspects of energy storage and transportation, the definition of fuel and energy vector is given.

Fuel

A fuel is generally considered as:

A. *"substance consisting largely of hydrocarbons, derived from the decay of organic materials under geological conditions of high pressure and temperature, include coal, petroleum, and natural gas"*

But "fuel" could also have a more general definition:

B. *"substance that produces useful energy when it undergoes a chemical or nuclear reaction"*

This second definition give space to a misleading association between fuels and energy vectors.

Primary energy resources

Primary energy resources are:

"energy resources directly available in nature"

They can be classified into two different families:

- Renewable resources can be harvested in the environment by natural processes and can be replaced or replenished in the same or less amount of time as it takes to draw down the supply.
- Non-renewables resources do not renew themself at a sufficient rate for sustainable economic extraction in meaningful human time-frames, it correspond to fossil fuels.

Energy vector

A good definition of energy vector is the one proposed by (22):

"An energy vector allows to transfer, in space and time, a quantity of energy"

Energy vectors allow to make energy available for use at a distance of time and space from the source, intended as the point of availability of the primary resource in nature or energy vector in the case of energy vector transformation.

Two important energy vectors that could find application on-board ships are:

- electricity
- hydrogen

Both of them are energy vectors but not primary energy resources. This is an important difference and innovation in the maritime sector since up to now, only energy vectors of the fossil fuel family has been used and considered. International and national rules and standard (IMO, IEC, Classification Societies Guidelines) always refer indifferently to fuel as fossil fuel or hydrogen, while electricity is generally specified as such.

When referred to hydrogen technology therefore, it is observed that generally the second definition of fuel (definition B) is considered, leaving to adjectives the task to distinguish between primary resources fuel or non-primary resources fuel (namely hydrogen). The first is indicated as *primary fuel* or *raw fuel* while the second is labelled as *fuel* or *fuel cell fuel*.

For this reason hereafter with the term *"fuel"* a subsection of the energy vectors will be considered, compatible with the chemical definition of fuel (definition B) that comprise fossil fuel and alternative fuels among which hydrogen.

2.1.1 Assessment of the energy vectors (fuels) characteristics

FUEL SPECIFICATIONS

		I									II		II	IV	V
#		F0	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13
NAME		MGO	MDO	IFO		HFO	LSMFO		GAS TURBINE FUEL		LPG		METHANOL	NG	H2
TYPE		DMA	DMB-DFB	RMB30	RMG380	RMG700	ULSFO	LS380	DMT2	RMT4	PROPANE	BUTHANE		Methane	
note							from 01/15 0.1% in SECA								
	unit														
HHV	MJ/kg	44.81	44.53	42.94	42.42	42.42	43.80	43.26	44.76	41.85	50.35	49.50	22.70	55.50	141.80
LHV	MJ/kg	41.84	41.60	40.05	39.62	39.62	40.79	40.34	41.53	38.52	46.35	45.75	19.93	50.00	120.97
Chemi. Structure	-	C8 to C25	C8 to C25	C8 to C25	C8 to C25	C8 to C25	C8 to C25	C8 to C25	C8 to C25	C8 to C25	C3H8	C4H10	CH3OH	CH4	H2
Physical State	NTP	Liquid	Liquid	Liquid	Liquid	Liquid	Liquid	Liquid	Liquid	Liquid	Gas	Gas	Liquid	Gas	Gas
Flash Point	°C	60	60	60	60	60	60	60	60	60	-104	-60	12	<0	<0
Density	kg/m^3	890	900	960	991	991	960	991	880	996	2.417	2.709	748.36	0.679	0.0852
Viscosity	mm^2/s	6	11	30	380	700	~30	~380	5.5	55	-	-	-	-	-
Sulphur	% m/m	1	1.5	3.5	3.5	3.5	0.1	1.5	1.3	4.5	-	-	-	-	-
Water	% v/v	0.3	0.3	0.5	0.5	0.5	0.5	0.5	0.5	1	-	-	-	-	-
Ash	% m/m	0.01	0.01	0.07	0.1	0.1	0.07	0.1	0.1	0.15	-	-	-	-	-
Pour Point Winter	°C	-6	-6	0	30	30	30	30	0	45	-	-	-	-	-
Pour Point Summer	°C	0	0	6	30	30	30	30	6	45	-	-	-	-	-
CO2 content	$kgCO_2/kWh$	0.25	0.25	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.22	0.22	0.25	0.18	
Auto ignition	°C	300	300	300	300	300	300	300	300	300	470	405	480	560	565
Flamability	% v/v	-	-	-	-	-	-	-	-	-	2.5 – 9.6	1.8 – 8.4	6 – 36	4.4 – 17	4 -75
Boiling point	°C	-	-	-	-	-	-	-	-	-	-42	-1	64.7	-161.5	-252.9
Hazards	-	-	-	-	-	-	-	-	-	-	Heavier than air	Heavier than air	Toxic	-	-
Drop-in	-	yes	yes	yes	yes	yes	yes/no	yes	yes	yes	no	no	no	no	no
Cost	$/mt	550	-	-	300	300	550	430	-	-	370	-	400	850	3720
Energy Density	kWh/l	10.34	10.40	10.68	10.91	10.91	10.88	11.11	10.15	10.66	0.03	0.03	4.14	0.009	0.003
Specific Energy	kWh/kg	11.62	11.56	11.12	11.00	11.00	11.33	11.21	11.54	10.70	12.88	12.71	5.54	13.89	33.60

MGO	Marine Gas Oil	Fuels are devided into five groups:	
H2	Hydrogen		
HFO	Heavy Fuel Oil	I	Fuel Oil
IFO	Intermediate Fuel Oil	II	Petroleum Gases
LPG	Liquified Petroleum Gas	III	Methanol
LSMFO	Low Sulphyr Fuel Oil	IV	Natural Gas
MDO	Marine Diesel Oil	V	Hydrogen
NG	Natural Gas		

Table 7. Energy vectors specifications (23) (24) (25) (26) (27)

The assessment of the energy vectors for marine application required the collection of information on chemical and physical properties of “fuels” and the evaluation of important comparison parameters. Data has been collected for all the Fuel Oil (FO) typology available for marine applications, analysing the differences between them in terms of fuel characteristics and on-board fuel usage, with particular references to Low Sulphur Fuel Oil (LSFO). Other fuel categories have been analysed:

I. Fuel Oil (DMA, DMB, RMB30, RMG380,RMG700, ULSFO, LS380, DMT2, RMT4);

II. LPG (Propane, Butane).

III. Methanol;

IV. Natural Gas (Methane);

V. Hydrogen.

Even the passage between standard FO to ULSFO require important upgrades of the fuel processing system in order to make the fuel compatible with the ICE. The same apply for all the fuel categories, with the exception of hydrogen, that even if could be burned inside ICE, will be considered only in conjunction with fuel cells due to high costs and low efficiency of H2 fuelled ICE as well as technical problems related to high temperatures.

Table 7 reports the results of the assessment. Among the collected parameters, the following have important meaning: *LHV* and *HHV*, *density*, *sulphur* content, *viscosity*, *drop-in*, *energy density* and *specific energy*. The first two parameters gives an indication of the energy content of the energy vector. These parameters are connected to the specific weight of the fuel, from this point of view hydrogen is the most energy dense fuel. The density values refer to a temperature of 15℃ and atmospheric pressure, also known as normal temperature and pressure. From the density value it’s possible to distinguish between liquid and gaseous fuels and have a hint of the related storage difficulties. Viscosity is an important value for ICSs and ship fuel processing unit using FO. Heavy Fuel Oils (HFO) in particular are characterized by high viscosity that require high temperature to be managed and used. ICE and fuel systems designed to operate with high viscosity HFO are not compatible with low viscosity fuel oil. ULSFO in particular, even if presents higher viscosity with respect to traditional high sulphur ISO 8217, are blend products with low viscosity and high pour point that require the use of different lubes and fuel treatment systems (chillers). For this reason have been considered not completely drop-in. The former is identified as the interchangeable characteristic of a fuel, with complete compatibility with ICE and fuel treatment system. Alternative fuels are not drop-in fuel but have a low sulphur content, that represent the main driver to the adoption of alternative fuels. Finally, the most significant value presented in Table 7 is represented by energy density and specific energy. They have been evaluated considering LHV energy content and the fuel density. These parameters refer to NTP conditions, and show the reason why most of the alternative fuels could not be stored and transported on-board in natural conditions, but other medium are to be used.

Energy Medium

Energy vectors are defined on the base of their chemical and physics characteristics at standard or normal conditions. In order to be comparable, the same conditions have to be maintained for all the energy vectors. But due to the poor energy density (kWh/l) of alternative fuels, high pressures or low temperatures are used to transport these energy vectors. For this reason a definition of a energy medium is given:

“A energy vector condition that makes possible the transfer of energy from one location to another with high energy density”

LNG for example is considered a medium used for the transportation of natural gas. Energy medium present different energy density and specific energy from energy vectors due to different physical conditions only.

Storage systems analysis

In the following an analysis of the properties of different fuel storage system is presented. The storage system characteristics depend on the energy medium characteristics. For this reasons an assessment of the possible energy medium for each fuels has been conducted. Table 8 resume the results of the assessment, showing the connection between the fuel categories previously identified with the energy medium and the storage systems.

FUEL	I- FO	II-LPG	III-METHANOL	IV-NG	V-H2

#	S1	S2	S3	S4	S5	S6	S7	S8	S9
MEDIUM	FO	CNG	LNG	LPG	METHANOL	CH2	LH2	LH2	MH
STORAGE	Bare Tank	Compressed	Cryogenic	Pressurized	Bare Tank	Compressed	Criogenic	Cryo/Compr	Bare Tank
note		200 (bara)	-160 °C	(1bara)		700 bar	- 252 °C	350 bar/-252 °C	Intermetallic

Table 8. Fuel category and fuel storage connections

I. Fuel Oil (FO), whatever the kind, is a liquid fuel that can be stored inside a bare tank.

II. Liquefied Petroleum Gas (LPG) is a category that already define the energy medium, either propane or butane, are gases that are maintained liquid with a pressurized system.

III. Methanol is a liquid fuel that can be stored inside a bare tank at NTP conditions.

IV. Natural Gas (NG), due to the low energy density at NTP, it is usually transported as Compressed Natural Gas (CNG) or Liquid Natural Gas (LNG). The first energy medium uses high pressure, the second uses low temperature.

V. Hydrogen (H2), being the object of the research, various storage systems have been analysed. Compressed Hydrogen systems (CH2), Liquid Hydrogen systems (LH2), Cryo-Compressed Hydrogen systems (CCH2), Metal Hydride systems (MH). CCH2 systems use liquid hydrogen as medium.

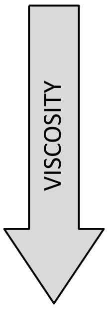
Table 8 indicates the temperature or pressure of the energy medium, that represent the operative condition that have to be maintained by the storage system. Among the nine energy medium/fuel storage systems that have been identified, two of them have been discarded due to the poor performances or the limited technology development. CNG is a standard storage system for land application where usually 200 bar steel cylinders are used. However, large energy storages require high energy density and specific energy that could be reached only using LNG. CCH2, has been discarded because it has been evaluated too complex and costly for a marine application.

In the following, each storage system will be analysed. The analysis will consider the characteristic of the storage tank and of the related fuel process unit, required to deliver the fuel to the generator with the right conditions. FO processing volume and weight have not been considered for evaluation of the storage density, while for the alternative fuels it has been considered only partially. The reason rely on the difficulties on the data collection.

S1-Fuel Oil

Bunker fuel or bunker crude is technically any type of fuel oil used aboard vessels. It gets its name from the tanks on ships and in ports where it is stored; in the early days of steam ships they were coal bunkers but now they are bunker fuel tanks.

HFO is the most used fuel aboard ships. There are many types of fuel. In the maritime field a dedicated classification for fuel oils is used:



- MGO (Marine gas oil) - roughly equivalent to No. 2 fuel oil (Numbers refer to the United States of America classifications), made from distillate only
- MDO (Marine diesel oil) - A blend of heavy gasoil that may contain very small amounts of black refinery feed stocks, but has a low viscosity up to 12 (cSt) so it need not be heated for use in internal combustion engines
- IFO (Intermediate fuel oil) A blend of gasoil and heavy fuel oil, with less gasoil than marine diesel oil
- MFO (Marine fuel oil) - same as HDO (Heavy Diesel Oil, just another "naming")
- HFO (Heavy fuel oil) - Pure or nearly pure residual oil, roughly equivalent to No. 6 fuel oil

Since the 1980s the International Organization for Standardization (ISO) has been the accepted standard for marine fuel oils (bunkers). The standard is listed under number ISO 8217, with recent updates in 2010 and 2017. The standard divides fuels into residual and distillate fuels. The most common residual fuels in the shipping industry are RMG and RMK. The differences between the two are mainly the density and CCAI. Both correspond to the "Residual" classification of fuels given by ISO 8217 and 8216-99 and generally are delivered at 380 or at 700 centistokes.

The Calculated Carbon Aromaticity Index (CCAI) and Calculated Ignition Index (CII) are two indexes that describe the ignition quality of residual fuel oil, and CCAI is especially calculated for marine fuels. These indexes are used in the USA classification standard that rate fuels into 6 types. Despite this, marine fuels are still quoted on the international bunker markets with their maximum viscosity (which is set by the ISO 8217 standard) due to the fact that marine engines are designed to use different viscosities of fuel. Below a list of the fuels most frequently quoted is given in order of cost, the least expensive first.

- IFO 380 - Intermediate fuel oil with a maximum viscosity of 380 centistokes (<3.5% sulphur*)
- IFO 180 - Intermediate fuel oil with a maximum viscosity of 180 centistokes (<3.5% sulphur*)
- LS 380 - Low-sulphur (<1.0%**) intermediate fuel oil with a maximum viscosity of 380 centistokes
- LS 180 - Low-sulphur (<1.0%**) intermediate fuel oil with a maximum viscosity of 180 centistokes
- LSMGO - Low-sulphur (<0.1%*) Marine Gas Oil - The fuel is to be used in EU Ports and Anchorages. EU Sulphur directive 2005/33/EC
- ULSMGO - Ultra-Low-Sulphur Marine Gas Oil - referred to as Ultra-Low-Sulphur Diesel (sulphur 0.0015% max) in the US and Auto Gas Oil (sulphur 0.001% max) in the EU. Maximum sulphur allowable in US territories and territorial waters (inland, marine and automotive) and in the EU for inland use

- ULSFO - Ultra-Low-Sulphur Fuel Oil - refer to a category of FO introduced from the first January of 2015 after the enter into force of IMO 0.1% limitation in ECA zones. Made of blend fuels are generally produced in the ISO 8217 grades DMA, DMB, RMA
- MDO - Marine diesel oil
- MGO - Marine gasoil

(*) The sulphur content is regulated by the IMO MARPOL Annex 6. From 2015 the SECAs limits passed from <1.0% to <0.1%,

(**) It is commonly considered Low Sulphur a concentration <1,0% while Ultra Low Sulphur has a concentration of <0.1%. Today are usually confused since LS limits are not tolerated into SECA areas;

In the following study different types of Heavy Fuel Oil have been considered through the development of a comparative assessment of the main technical parameters able to influence the performance of the ship in terms of bunkering, storage and utilization.

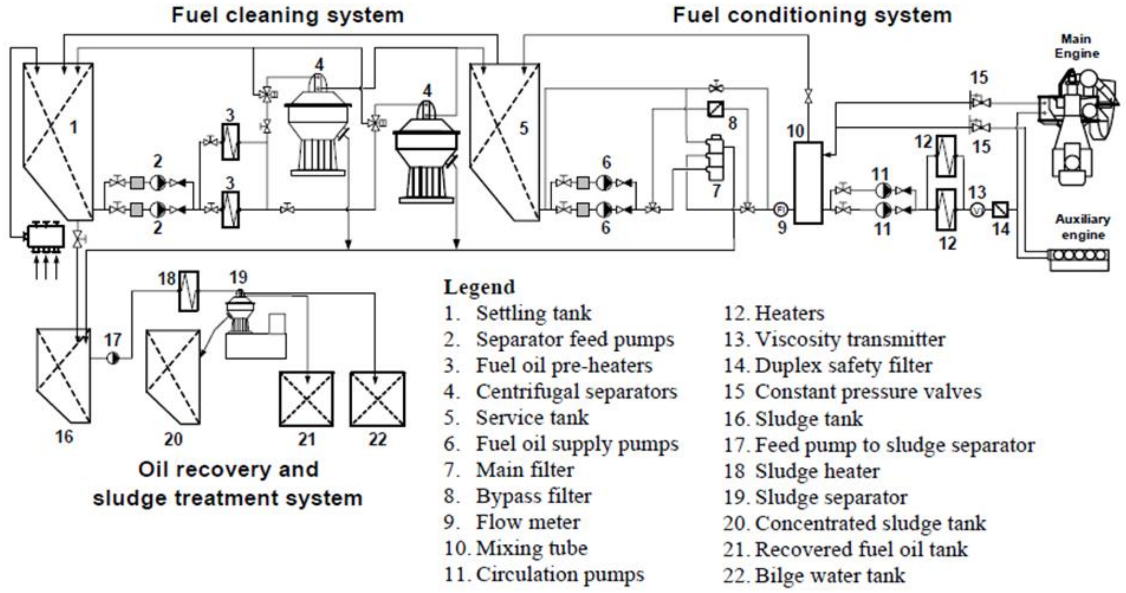


Figure 9. Fuel Oil treatment system

Figure 9 (28) shows a typical fuel oil system of ships running with HFO. It is composed by two main parts, the fuel cleaning system and the fuel conditioning system. Distillate fuels don't require the fuel cleaning as well as alternative fuels. The volume and weight of the auxiliary system has not been evaluated due to the difficulty on the data collection, but Figure 9 is able to show the complexity of the FO treatment system and give a hint of the required volumes. The reason why FO represent the present marine solution that ship owners want to keep is that it has important advantages from the economic side:

- Less expensive fuels
- Already available infrastructure
- Well developed and established technology on-board the majority of ships (drop-in)

On the contrary, HFOs suffer the presence of not admissible amount of sulphur that prevent their use in the future without an exhaust treatment system able to capture the excess. HFOs are mostly produced by atmospheric and vacuum distillation that are the first steps in the manufacture of fuel oil (19). The largest part of refineries are based just on this process. The present oil industry is not able to produce the large amount of highly purified LSFO required by shipping in the next future in case of a major shift to this solution from the world fleet. The required investment could also be costly considering the future reduction of oil extraction (oil pick) and consumption due to the adoption of new technologies and fuels.

International and National legislation are imposing the use of low sulphur fuel oils in different areas with different calendars. These kinds of fuels are required inside the Sulphur Emission Controlled Areas (SECA) and Emission Controlled Areas (ECA (as explained in Chapter 1.5) as also in ports and inland waters. Table 9 (24) resume the current SO_x limit imposed by IMO Marpol Annex XI.

Sulphur content	**2015 -->**	**2020 -->***	**Act**
Ships at berth	0.001	0.001	Marpol and EU
Inland waterways	0.001	0.001	Marpol and EU
Outside SECAs	0.035	0.005	Marpol and EU
Inside SECAs	0.001	0.001	Marpol and EU
Ro-Pax (outside SECAs)**	0.015	0.001	EU

*May be postponed to 1 January 2025
**only in Member States' territorial seas as established by Directive 2005/33/EC

Table 9. Sulphur limit content

Before 2015 distinction were made between LSFO (<1.0% Sulphur) and ULSFO (<0.1% Sulphur). Today, in order to respect the SECA limitation only ULSFO or MDO should be used. MDO has a higher cost with respect to ULSFO but are some time preferred to the later one because of the poor winter characteristic of ULSFO. Indeed, these new marine fuel types are not of the distillate type, but new blends. Among the different characteristics of ULSFO there are some that interact with the performance of the Internal Combustion Engines (ICEs) (25):

- Higher viscosity than distillate equivalent
- Low viscosity range available
- Some of these fuels might contain cat-fines (Al+Si)
- Some of these fuels have high pour points
- Compatibility to other fuels could also be an issue

These characteristics require the use of different lubrications and ICE set parameters. The IMO Marpol rules require to change over from HFO to ULSFO before arrival in SECAs. The effect on a HFO fuel system and engine when operated on ULSFO needs to be considered. For example using only one service tank would require long time of blended fuels before reaching the required sulphur content at the engine. This would result in higher costs (higher use of ULSFO) that could make advantageous the use of two different service tanks, that on the contrary will require larger volumes on-board and the ship fuel system modification. In the following a short analysis on the use of ULSFO is given.

1) High viscosity and the presence of cat fines particles require a different fuel treatment. This problem connected to the long time of blended fuels in the case of singular service tank drive towards a double service tank solution. Figure 10 (29) shows an example of fuel system for a ship equipped with ULSFO tanks. The overall complexity and system volume is almost doubled.

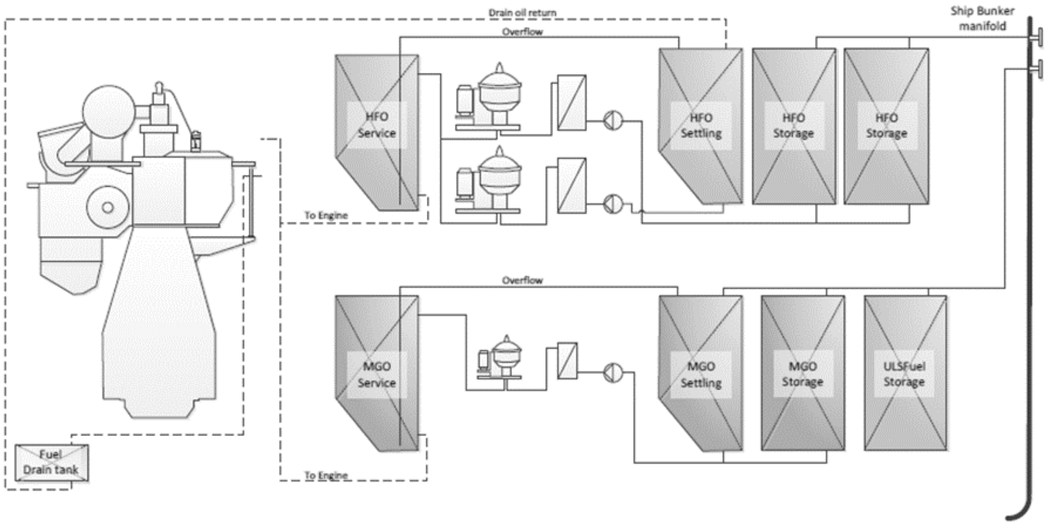


Figure 10. HFO/ULSFO fuel conditioning system

2) ULSFO has high winter pour point that require high fuel system temperature to pour the fuel from the tanks. At the same time ULSFO are produced blending HFO with low sulphur distillate fuels, for this reason they have low viscosity. Today, external fuel systems on-board are often designed to have an optimum operation on HFO, which means that the temperature is kept high. When running on low-viscosity fuels, the temperature of the fuel system must be as low as possible to ensure a suitable viscosity at engine inlet. Low-viscosity fuels challenge the function of the fuel pump in three ways:

1. Breakdown of the hydrodynamic oil film, which could result in seizures
2. Insufficient injection pressure, which results in difficulties during start-up and low-load operation
3. Insufficient fuel index margin, which limits acceleration

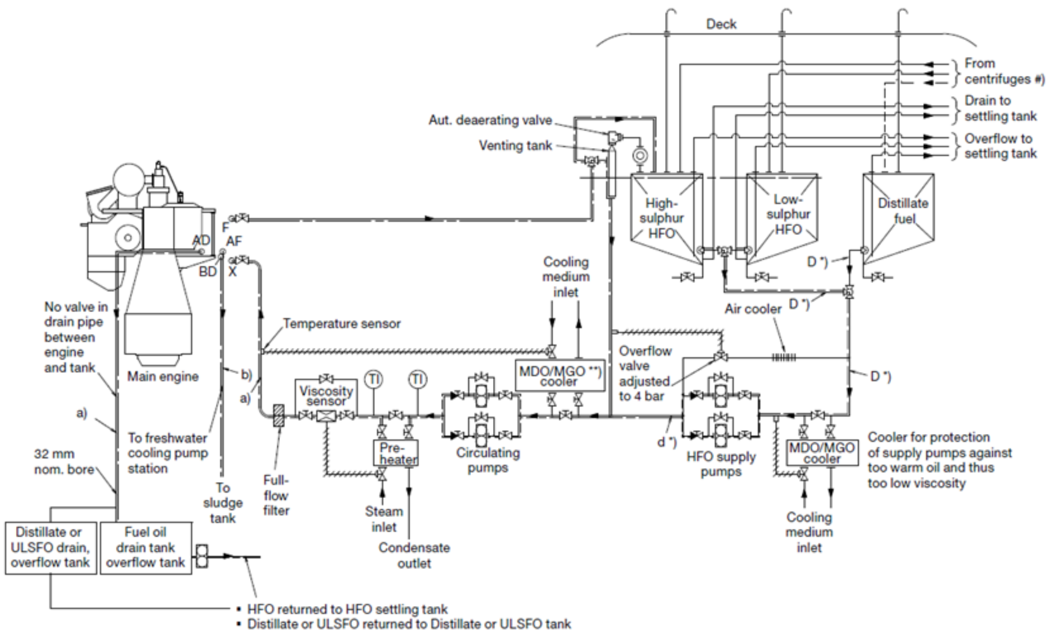


Figure 11. Complete fuel conditioning system, with double service tank (HFO and ULSFO), cooling system and viscosity sensor

It is difficult to optimise all of these factors at the same time. To have some margin for safe and reliable operation and to maintain the required viscosity at engine inlet (~2 cSt), installation of coolers (or chillers) will be necessary in those fuel systems which do not have these (Figure 11 (30)).

3) Operating the engine with an unmatched (Basic Number) BN/fuel sulphur content could increase the risk of either scuffing or excessive corrosive wear. Therefore, running on low sulphur fuel is considered more complex due to the relationship between liner corrosion and scuffing resistance, dry lubrication properties from elements in the fuel (or lack of same), the interaction between the BN in the cylinder oil and the detergency level, possible surplus of alkaline additives, the piston ring pack, etc. Low BN oils should be chosen for low- sulphur fuels, and high-BN oils for high-sulphur fuels.

- BN 40-50, Sulphur <3.5%
- BN 60-70, Sulphur >2.5%

Figure 12 (31) shows an example of double lube oil system to operate the same ICE with HFO or ULSFO.

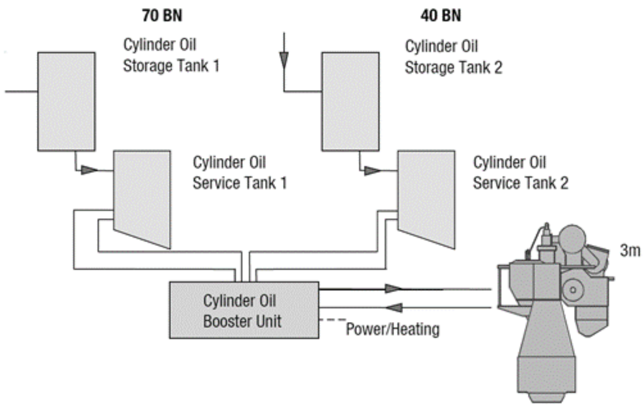


Figure 12. Fuel system with cooler in the circulating system and also the supply system. Today the pumps in the supply system are made to handle fuels with less

3) Blend compatibility with other fuel exacerbate the problem of a single service tank, even for the compatibility between MFO and MGO as indicated by standard ASTM D4740-4. Some fuels are not compatible and as fuel continue to leak from the engine, considerations should be made to assure that the drain oil do not contaminate the settling tanks. Figure 13 (29) elaborated from ASTM D4740-4 standard, immediately show the poor compatibility between HFO and ULSFO.

In conclusion, the possibility to shift from high sulphur FO to low sulphur FO to comply with the SECA limits represent the first choice for a ship operator since it permit the use of ICE technology without the necessity of the exhaust gas treatment. However this solution doesn’t come without side effects. Among all, in the following are presented some of the most important:

- Not sufficient availability of LSFO for whole ship fleet, high price
- Necessity to have two separate lube systems
- FO compatibility requires the use of two different service tanks
- Viscosity compatibility requires the use of cooler or chiller
- Higher LSFO price

Considering pro and con, this solution result to be level out with other solutions, in particular exhaust gas treatment systems seems to be competitive in terms of costs, volume and weight when ICE technology and FO are considered as primary choice.

Fuel	ULSFO1	ULSFO2	ULSFO3	ULSFO4	ULSFO5	ULSFO6	ULSFO7	MGO1	MGO2	MGO3	MGO4	MDO1	MDO2	MDO3	HFO1	HFO2	HFO3	HFO4	HFO5	HFO6	HFO7	
ULSFO1		2a	10 a	20 a				4a	13 b			6a			1a				1b	3a	1c	
ULSFO2	2a		9a					1+ 2+ 3	14 b			5			8a		4		2b	6	2c	
ULSFO3	10 a	9a		22 a				13 a	15 b			12 a			11 a				3b		3c	
ULSFO4	20 a		22 a					19 a	17 b			21 a	23 a		17 a	18 a			5b		5c	
ULSFO5																						
ULSFO6																						
ULSFO7																						
MGO1	4a	1+ 2+ 3	13 a	19 a					16 b						5a	16 a			4b		4c	
MGO2	13 b	14 b	15 b	17 b				16 b				18 b	21 b		23 b	19 b	20 b	22 b	10 b		c	
MGO3																						
MGO4																						
MDO1	6a	5	12 a	21 a					18 b						7a				6b		6c	
MDO2				23 a					21 b										9b		9c	
MDO3																					10 c	
HFO1	1a	8a	11 a	17 a				5a	23 b			7a				15 a			12 b		11	
HFO2				18 a				16 a	19 b						15 a				7b		7c	
HFO3		4							20 b										8b		13 c	
HFO4									22 b										11 b		14 c	
HFO5	1b	2b	3b	5b				4b	10 b			6b	9b		12 b	7b	8b	11 b			15 c	
HFO6	3a	6																				
HFO7	1c	2c	3c	5c				4c	c	c		6c	9c	10 c	11 c	7c	13 c	14 c	15 c			

Figure 13. Fuel compatibility from ASTM D4740-4 standard

S2-Compressed Natural Gas

Compressed Natural Gas (CNG), is a standard energy medium in the energy sector. A mix of gas composes natural gas, generally, 96% is methane. Other components are ethane, carbon dioxide, propane, butane, nitrogen and other components in small percentage. The CNG medium density at 15 (°C) and 200 (bara) is of 212 (kg/m^3), pure methane has a density of 199 (kg/m^3) at the same conditions (32).

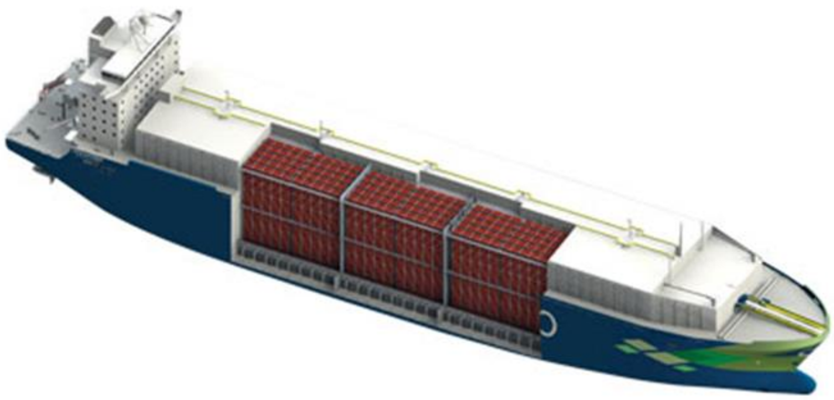


Figure 14. CNG32000 Project of Fincantieri

Only one marine project dedicated to the transport of large quantities of NG has been found, the CNG32000 project of Fincantieri (33), Figure 14. Its total CNG transport capacity during a single voyage under standard conditions would be around 6.34 MMcm (Million cubic meters) at 166 (bar) and a temperature of 25 (°C). This would be stored in pressure steel vessels grouped together in around 500 racks, stationed in 10 cargo holds (50 racks each). A preliminary analysis gives as result for type I tanks the following figures:

$$Energy\ Density\ (kWh/l) = 1.67\ (@200\ bar);\ 1.40\ (@166\ bar)$$

$$Specific\ Energy\ (kWh/kg) = 0.96\ (@200\ bar);\ 0.84\ (@166\ bar)$$

These performances have been considered poor in comparison with the LNG system ones, for this reason it has been chosen to discard this energy vector storage from the analysis.

S3-Liquified Natural Gas

S3 - LNG								
Type	**Pressure**	**Temperature**	**LNG**	**Energy**		**tot Weight**	**Int Volume**	**tot Volume**
-	**bar**	**°C**	**kg**	**MJ – LHV**	**kWh – LHV**	**kg**	**l**	**l**
Wartsila LNG pac 284	2	-160	115,200.0	5,760,000.0	1,600,001.3	254,100.0	284,000.0	432,681.7
Type	**ED**	**SE**						
-	**kWh/l**	**kWh/kg**						
Wartsila LNG pac 284	4.07	6.93	LNG system volume and weight (without all BoP)					
	3.70	6.30	LNG system volume and weight (with all BoP)					
	5.63	13.89	LNG volume and weight					
	2.87	6.30	with respect to the storage room					

Table 10. LNG storage system performance

Note:

- *tot Weight: The Wärtsilä LNG pac 284 is indicated to weight 231 (t). The BoP has been estimated in 10% of the full tank weight, for a total weight of 254 (t).*
- *tot Volume: The same approximation has been made to evaluate the BoP volume, 10% of the external tank volume calculated from the Wärtsilä LNG pac 284 datasheet.*
- *ED (kWh/l) without BoP: The value has been evaluated as the ratio between the energy content (kWh) and the external volume equal to 393.3 (m^3).*
- *SE (kWh/kg) without BoP: The value has been evaluated as the ratio between the energy content (kWh) and the Wärtsilä LNG pac 284 datasheet weigh equal to 231 (t).*
- *ED (kWh/l) with BoP: The value has been evaluated as the ratio between the energy content (kWh) and the total volume.*
- *SE (kWh/kg) with BoP: The value has been evaluated as the ratio between the energy content (kWh) and the total weight.*
- *ED (kWh/l) LNG: The value has been evaluated as the ratio between the energy content (kWh) and the internal tank volume indicated in the Wärtsilä LNG pac 284 datasheet equal to 284 (m^3).*
- *SE (kWh/kg) LNG: The value has been evaluated as the ratio between the energy content (kWh) and the LNG weight. The former has been evaluated considering LNG density and internal tank volume.*
- *ED (kWh/l) room: The value has been evaluated as the ratio between the energy content (kWh) and the room volume indicated in the Wärtsilä LNG pac 284 datasheet equal to 556.5 (m^3).*
- *SE (kWh/kg) room: The value has been considered equal to SE with BoP.*

LNG is generally considered the most important alternative fuel. There are many reasons that lay behind the progressive success of this energy vector in the marine sector. Leaving apart the political ones, LNG is considered a good alternative fuel to FO because there is a good availability at a good price, and obviously, it allows the compliance with Sulphur Emission Controlled Area (SECA) sulphur requirements. Moreover ICE OEMs succeed in the development of NG fuelled ICE and of dual fuel ICE, able to run on FO and LNG. Considering the problems related to the use of ULSFO and exhausts gas treatment system, LNG systems with ICE represent a valid alternative solution. The main problems related to the use of LNG rely on the absence of a distributed infrastructure and on the poor on-board storage capacity. The former has been the objective of the analysis, with the goal to assess the possibility to use LNG as a energy vector for the production of hydrogen on-board to feed low temperature fuel cells or its direct use inside a high temperature fuel cell, namely SOFC.

The analysis considered the performance of the Wärtsilä LNG pac 284 (34), a storage system designed to operate with dual fuel Wärtsilä ICE (35). According to the current IMO IGF code, the LNG fuel tanks could be of "Membrane Type" or "independent". The former is distinguished among three different types: Types A, B, or C. The Wärtsilä LNG pac 284 is of the C type, has been chosen because is considered the most mature technology at the present. Figure 15 shows an example of the LNG pac system layout.

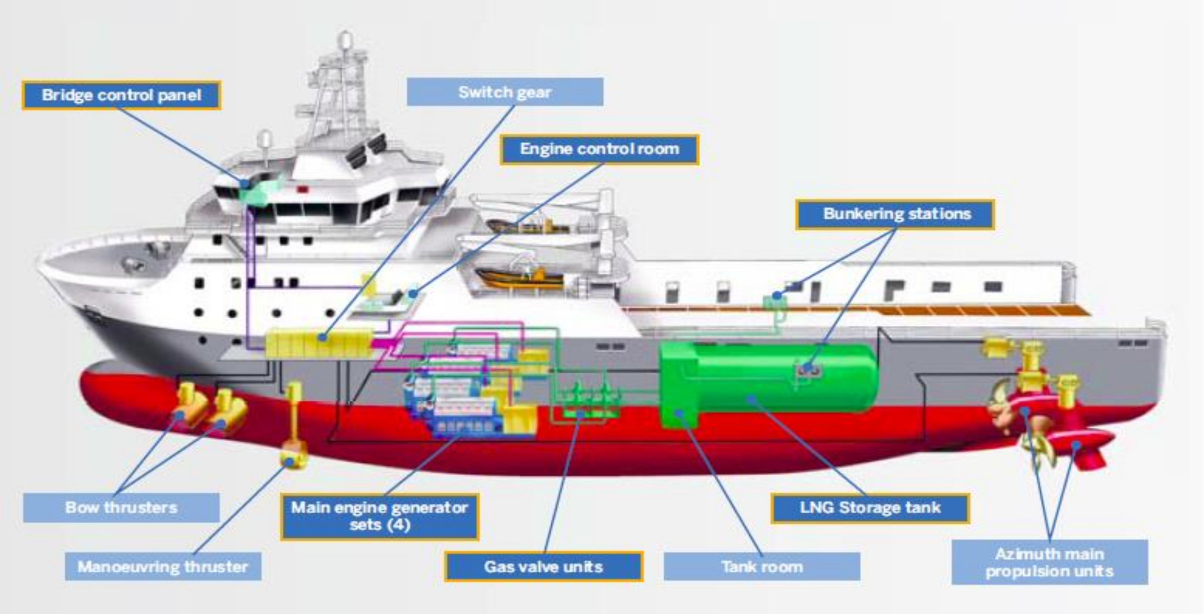


Figure 15. LNG pac system layout

Many studies (36) (37) assessed the use of LNG on-board ships in conjunction with ICEs. The performance results to be in line with the expectations and, as will be demonstrated in the comparative study, are the highest ones among the medium/storage systems that have been analysed. In Figure 16 a simplified P&ID scheme of the LNG pac system is presented. It shows the main components and gives an idea of the relatively simple required installation. The difficulties rely on the extreme conditions at which the medium, LNG, should be kept: -160 (°C). The low temperature should be maintained for long period of time, otherwise the Boil-Off effect start to appear. The former does not represent a problem as long as the gas is used, but it rises safety problems related to the internal tank pressure. Type C tanks are not able to withstand high pressure (5 bara max), so that in case of emergency natural gas is released in the environment. The gas expulsion represents an extreme safety measure that doesn't occur during normal operation. Therefore, slip methane has been recorded from ICE. If well managed, boil off and slip methane don't represent a safety issue, but they represent a serious environmental problem as observed during parallel studies (9) (38).

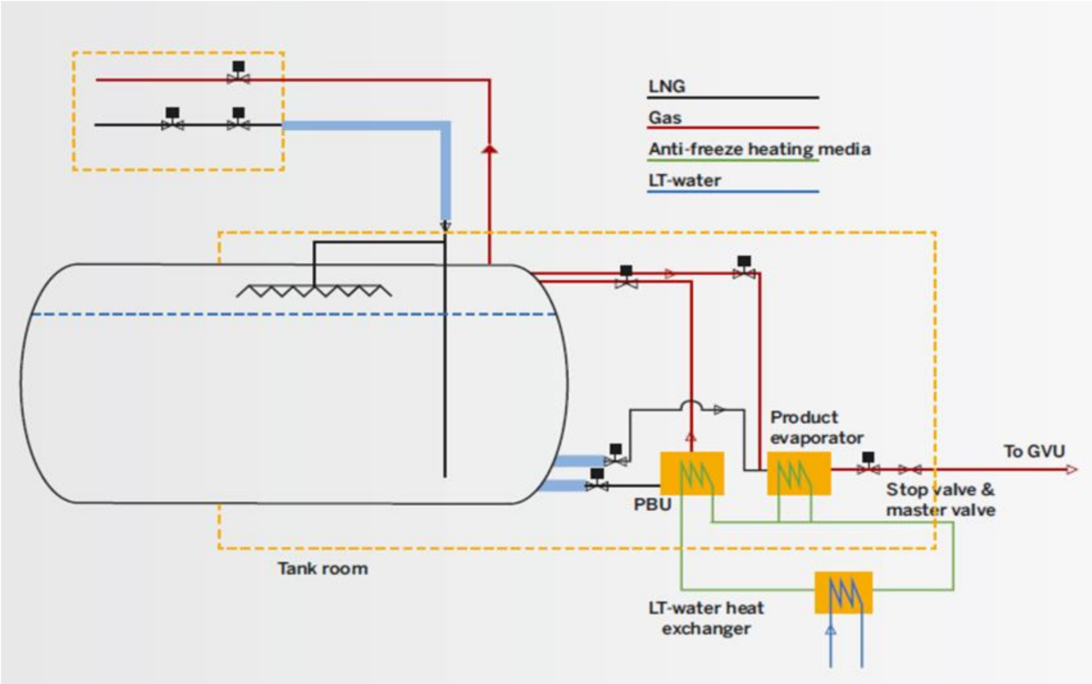


Figure 16. Simplified P&ID scheme of the LNG pac system

IMO resolution MSC 285(86) initially introduced the guidelines for the installation of LNG systems on-board ships. From first January 2017 the IMO IGF code provides an international standard for ships using low-flashpoint fuel, other than ships covered by the IGC Code.

From the IMO ECA emission reduction point of view, LNG is able to fulfil almost completely to the limitations when used inside ICE. Table 11 (39) shows the general emission reduction achieved using DF engines an LNG with respect to Tier II engines operated with HFO. From that table it is possible to observe that the Nitrogen Emission Controlled Area (NECA) compliance is not achieved without Selective Catalytic Reduction (SCR) or Exhausts Gas Recirculation (EGR) systems.

	NOx	SOx	PM	CO2
LNG	20-30%	90-97%	90%	23%
*Compared to the Tier II engine operating on HFO, conventional fuel valve and HFO pilot oil				

Table 11. LNG compared emission reduction, compared to the Tier II engine operating on HFO

Other Dual Fuel (DF) ICE technologies though have been developed to comply with the NECA limits. Table 12 (38) shows a comparison between the most common DF technologies. Lean Burn Sparked Ignited (LBSI) and Low Pressure Dual Fuel (LPDF) engines are able to meet IMO Tier III requirements regarding NOx emissions.

Reduction factors compared to MGO	LBSI	LPDF*, 4-stroke Medium speed	LPDF, 2-stroke Slow speed	HPDF, 4-stroke, medium speed	HPDF, 2-stroke, slow speed
CO_2	25-28%	20-25%	20-26%	20-24%	20-24%
NOx	85-90%	75-90%	75-90%	25-30%	25-30%
SOx	>99%	98-99%	95-99%	95-97% **	95-97% **
Particulates	>99%	95-98%	95-98%	30-40%	N/A

*)Highest reduction factors for DF obtained with micro pilot ignition
**)Dependant of S-content in pilot fuel

Table 12. Emission factors from ICE fuelled with LNG

A study reported in (38) demonstrate that a trade-off for NOx emissions and methane- and CO emissions exist. By running lean, NOx emissions will be reduced, and as leaner an engine run as lower will NOx emissions become. However, at a point the total hydrocarbon and CO emission starts to rise and at very lean mixtures the combustion process becomes poorer resulting potential increase in total hydrocarbon and CO and significant reduction in engine efficiency. As previously said, even if today no requirements apply to methane emissions from ships, slip from gas engines are of concern, as it is a strong GHG gas with a GWP Factor 25 higher than CO2.

S4-Liquified Petroleum Gas

S4 - LPG								
Type	**Pressure**	**Temperature**	**LPG**	**Energy**		**tot Weight**	**Int Volume**	**tot Volume**
-	**bar**	**°C**	**kg**	**MJ – LHV**	**kWh – LHV**	**kg**	**l**	**l**
Propane tanks	18	20	139,200.0	6,451,920.0	1,792,201.4	254,870.0	240,000.0	447,014.4
Propane -IMO 5	18	20	13,920.0	645,192.0	179,220.1	23,170.0	24,000.0	-
Type	**ED**	**SE**						
-	**kWh/l**	**kWh/kg**						
Propane tanks	4.41	7.74	LPG system volume and weight (without all BoP)					
	4.01	7.03	LPG system volume and weight (with all BoP)					
	7.47	12.88	LPG volume and weight					
	3.81	7.03	with respect to the storage room, same proportion as for LNG tank room					

Table 13. LPG storage system performance

Note: The LPG storage system has been evaluated proportionally (10 times) to the propane IMO5 storage tank Tectainer T50 in order to design a energy storage of the same size of the Wärtsilä pac 284.

- *tot Weight: The value has been calculated considering 10 LPG tank of the type IMO5 Tectainer T50 to which the BoP value has been added, estimated in 10% of the full tanks weight.*
- *tot Volume: The value has been calculated considering 10 LPG tank of the type IMO5 Tectainer T50 to which the BoP value has been added, estimated in 10% of the full tanks volume.*
- *ED (kWh/l) without BoP: The value has been evaluated as the ratio between the energy content (kWh) and the external volume equal to 406.4(m^3).*
- *SE (kWh/kg) without BoP: The value has been evaluated as the ratio between the energy content (kWh) and the weigh equal to the weight of 10 IMO5 tank, 231.7 (t).*
- *ED (kWh/l) with BoP: The value has been evaluated as the ratio between the energy content (kWh) and the total volume.*
- *SE (kWh/kg) with BoP: The value has been evaluated as the ratio between the energy content (kWh) and the total weight.*
- *ED (kWh/l) LPG: The value has been evaluated as the ratio between the energy content (kWh) and the internal tank volume of ten IMO5 Tectainer T50 tanks equal to 240 (m^3).*
- *SE (kWh/kg) LPG: The value has been evaluated as the ratio between the energy content (kWh) and the LPG weight. The former has been evaluated considering LPG density and internal tanks volume.*
- *ED (kWh/l) room: The value has been evaluated proportionally to the ratio between room volume and LNG volume of the LNG storage system.*
- *SE (kWh/kg) room: The value has been considered equal to SE with BoP.*
- *A single_IMO5 Tectainer T50 have the following performance: ED (kWh/l)=4.41, SE (kWh/kg)= 7.74*

LPG is the acronym of "Liquefied Petroleum Gas" that is applied to mixtures of light hydrocarbons which can be liquefied under moderate pressure at normal temperature but are gaseous under normal atmospheric conditions. The main components of LPG are Propane (C_3H_8) and Butane (C_4H_{10}), mixed in different proportion. LPG is produced by the separation of heavier or denser hydrocarbons or from natural gas. LPG is derived from oil refining (40% of the world total; 75% of LPG in Europe) and natural gas processing (60% worldwide; 25% in Europe) (40).

LPG derived from oil-refinery may contain varying low amounts of olefin (unsaturated) hydrocarbons. LPG has no colour and no smell, usually a powerful odorant, ethyl mercaptan, is added so that leaks can be detected. Also LPG is a non-toxic gas with a density heavier than air. LPG is classified as a Low Flashpoint fuel, since propane and butane has flashpoint temperature respectively of -104 and -60 ºC, lower with respect to the standard level recognized by the IMO (60 ºC).

As automotive fuel, LPG is the largest alternative fuel in Europe, distributed through a network of 31,000 filling stations to fuel more than 7 million vehicles in 2007, with a global consumption from the automotive sector estimated in 22.9 million tonnes in 2010 (26). Chile is the world leader in marine use of LPG where 80% of salmon fishing boats use LPF as fuel (41).

The clean burning properties and portability of LPG provide an advantage in comparison with other low flashpoint fuels in the substitution of traditional fuels for ICEs. The main advantages of LPG are as follows:

- clean burning characteristics that gives reduced exhaust emissions
- both propane and butane are easily liquefied and stored in pressure containers
- well established distribution infrastructure worldwide, even if for land and automotive applications, not for ships
- cost competitive

Generally LPG is considered a safe fuel when treated with the right procedures. Among the main disadvantage of LPG the most critic is the higher density in respect with air, for this reason it tends to accumulate in low lying areas. Moreover, even if globally the combustion emission can be considered cleaner with respect to FOs, studies demonstrate a larger presence of un-combusted hydrocarbons and sometimes an higher presence of CO (42).

LPG can be maintained in liquid phase with moderate pressure (18 bar for 100% propane) and ambient temperature (20 ºC). Semi-pressurized tank (5-8 bar and 20 ºC) can also be used as well as refrigerated tanks (1 bar and -43 ºC for 100% propane). Present cargo ship are able to transport LPG with cargo capacity in the range of 30000 (m^3) and 100000 (m^3) for pressurized and liquid form respectively (26). Strict guidelines for the transportation of gases are stated in the International Maritime Dangerous Goods (IMDG) regulations for flammable gases (Class 2.1 goods), that apply also for the transportation of LPG. LPG can be used to fuel dedicated low flashpoint ICEs or Dual Fuel (DF) ICEs. At the present MAN Diesel & Turbo has developed and certified a commercial available propulsion DF engine. The combustion require the presence of a HFO pilot injection and compared to traditional diesel fuelled ICEs, the expected emissions of LPG fuelled engines is highly reduced as shown in Table 14 (39).

	NOx	**SOx**	**PM**	**CO2**
LPG	15-20%	90-97%	90%	20%
*Compared to the Tier II engine operating on HFO, conventional fuel valve and HFO pilot oil				

Table 14. LPG compared emission reduction, compared to the Tier II engine operating on HFO

LPG already represents an alternative to traditional FOs. In particular, small and medium size boats already use this fuel especially with outboard propulsion engines. The transportation of large quantities of propane and butane is considered state of the art and very recently, the first LPG ferry has been designed (General Electric LPG-fuelled COGES ferry). For these reason LPG could represent a valid solution although it comes with some drawbacks concerning the storage systems and environmental performances.

Figure 17 (26) shows a simplified P&ID scheme of a LPG fuel system designed by MAN Diesel & Turbo for the operation with the ME-GI ICE.

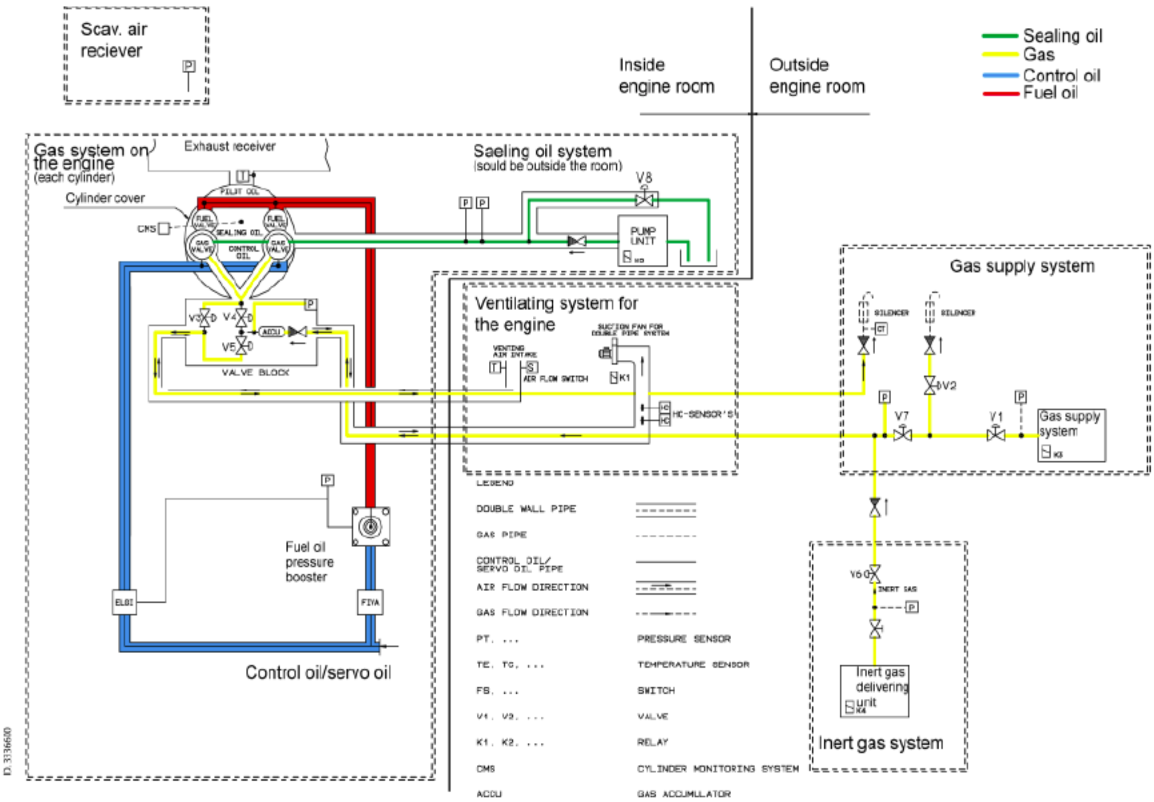


Figure 17. LNG fuel system (MAN Diesel & Turbo)

The scheme doesn’t show particular indication regarding the LPG tanks. Information on the LPG storage for ships are difficult to be found also because with the exception of the GE ferry example, no other ships design project using LPG as fuel has been found. Therefore, the analysis has been conducted considering standard IMO LPG container tanks, typically used to transport LPG. Due to the high pressure required by the energy medium, the storage vessel is required to be of cylindrical type. It is likely that configurations similar to the ones designed for LNG with large Type C vessels could be designed for LPG also. Indeed, a storage composed by 10 IMO 5 type LPG container tanks (Figure 18) have been considered to form a LPG storage able to store about 1.7 (MWh) of energy.

Figure 18. Tectainer T50 IMO 5 type LPG container tanks

As previously said, LPG tankers equipped with large storage tanks are available with pressurized, semi-pressurized and refrigerated tanks, indicating the possibility to use different storage systems as well. Table 13 report the analysis results considering the performance of a storage system composed by 10 IMO 5 type storage tank. The weigh and volume of the BoP have been considered equal to 10 % of the tank weight and external volume respectively, a value that has been extracted from the LNG system BoP at which the system has been compared.

S5- Methanol

S5 - METHANOL								
Type	**Pressure**	**Temperature**	**CH3OH**	**Energy**		**tot Weight**	**Int Volume**	**tot Volume**
-	**bar**	**°C**	**kg**	**MJ – LHV**	**kWh – LHV**	**kg**	**m3**	**l**
x	Atm	20	290,000.0	5,779,700.0	1,605,473.5	319,000.0	366,161.6	443,055.6
Type	**ED**	**SE**						
-	**kWh/l**	**kWh/kg**						
X	3.99	5.54	with respect to the CH3OH system volume and weight (without all BoP)					
	3.62	5.03	with respect to the CH3OH system volume and weight (with all BoP)					
	4.38	5.54	with respect to the CH3OH volume and weight					
	-	-	with respect to the storage room					

Table 15. Methanol storage system performance

Note: Methanol is liquid at NTP conditions, for this reason don't require a dedicated tank but could be stored inside a regular ship bunker tank. No weight for the tank has been considered.

- *tot Weight: The value has been considered equal to the fuel weight increased of 10% to consider BoP weight. A energy storage of the same size of LNG has been designed.*
- *tot Volume: The internal volume has been calculated from the fuel weight considering the fuel density at NTP, 366.2 (m^3). The external volume has been considered equal to the internal volume increased of 10% while the tot volume consider also the BoP volume equal to 10% of the external volume.*
- *ED (kWh/l) without BoP: The value has been evaluated as the ratio between the energy content (kWh) and the external volume.*
- *SE (kWh/kg) without BoP: The value has been evaluated as the ratio between the energy content (kWh) and the fuel weight, since no weight for the tank has been considered.*
- *ED (kWh/l) with BoP: The value has been evaluated as the ratio between the energy content (kWh) and the total volume.*
- *SE (kWh/kg) with BoP: The value has been evaluated as the ratio between the energy content (kWh) and the total weight.*
- *ED (kWh/l) LPG: The value has been evaluated as the ratio between the energy content (kWh) and the internal tank volume equal to the LPG volume.*

- *<u>SE (kWh/kg) LPG</u>: The value has been evaluated as the ratio between the energy content (kWh) and the LPG weight.*
- *<u>ED (kWh/l) room</u>: No room has been evaluated for LPG storage.*
- *<u>SE (kWh/kg) room</u>: No room has been evaluated for LPG storage.*

A short comparison analysis is given on the considered volumes of LNG, LPG and Methanol storage systems. LNG and LPG require cylindrical storage tanks, in the first case the tank is enveloped inside insulating material in order to maintain low temperature. The external volume calculated from the Wärtsilä datasheet shows that the external cylindrical tank is 40% larger than the internal tank volume. The geometric external volume though result to be 501 (m^3), 10% less voluminous of the room volume indicated by the datasheet. For LPG, the thickness of the cylindrical tank is limited and the external tank volume was not defined. The external volume has been considered equal to the geometric external volume of the tank (Figure 19). The ratio between the external volume and the internal volume of LNG and LPG tanks is of 76% and 69% respectively, similar. For this reason the right volume comparison between the two systems should be made between the room performance of LNG against the LPG system with BoP.

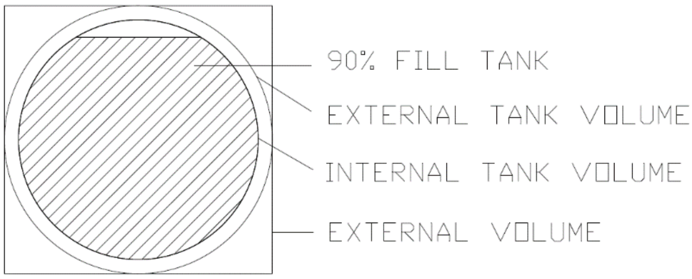


Figure 19. Tanks volume definitions

Even if the Methanol LHV is almost half of LNG or LPG, the system result to have similar total volumes. The fact is explained by the limited ratio between the external volume and the internal volume that has been considered for the systems, 10% in the case of Methanol, about 70% in the case of LNG and LPG. This value has been considered because Methanol is liquid at NTP, therefore it don’t require cylindrical storage tanks.

Traditionally, Methanol was produced by dry distillation of wood, from which it derived the name “wood alcohol”. The industrial synthesis of Methanol was developed quite early, and in first 19th Methanol was one of the products in a catalytic process. Today most of the Methanol on the market is produced from natural gas while coal is used for much of the production in China, mainly for domestic use.

Methanol properties and industrial use are well described in literature (43). Methanol as fuel for ships doesn’t need particular presentation since it already proved it’s performance (44). Wärtsilä (45) and MAN (46) already provides ICE able to work with Methanol as sole fuel or in dual fuel condition. Figure 20 shows a general installation scheme of a dual fuel system elaborated by MAN. It is possible to observe that at the present the fuel conditioning systems (settling tank and supply system) is installed on the main deck while the storage tank is represented by a regular ship tank, thanks to the liquid state of Methanol at NTP condition. The main concerns on the use of this fuel from the safety point of view is represented by its toxicity. The example is thought as a solution for dual fuel MAN ME-LGI ICE to be used inside ECA zones.

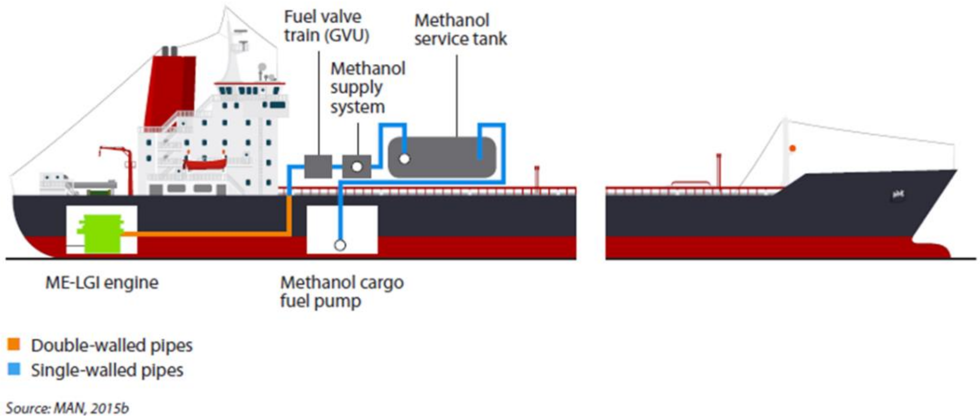


Figure 20. Dual fuel Methanol fuel conditioning system overview (MAN Diesel & Turbo)

Figure 21 shows a simplified P&ID scheme of the entire fuel system. To comply with safety issue, double walled pipes are used from the fuel conditioning system installed on the main deck to the ICE installed inside the engine room. The engine uses temperature-conditioned methanol at a fixed supply pressure and varying flow depending on the engine load. The methanol low flashpoint fuel supply system (LFSS) will have to supply this fuel to the engine while complying with the requirements described regarding temperature, flow, pressure and ramp-up capabilities. The fuel valve train connects the LFSS with the engine through a master fuel valve (MFV) arranged in a double block and bleed configuration. For purging purposes, the valve train is also connected to a nitrogen source. Typically, the valve train will be placed outside the engine room above the weather deck to avoid the need for double safety barriers.

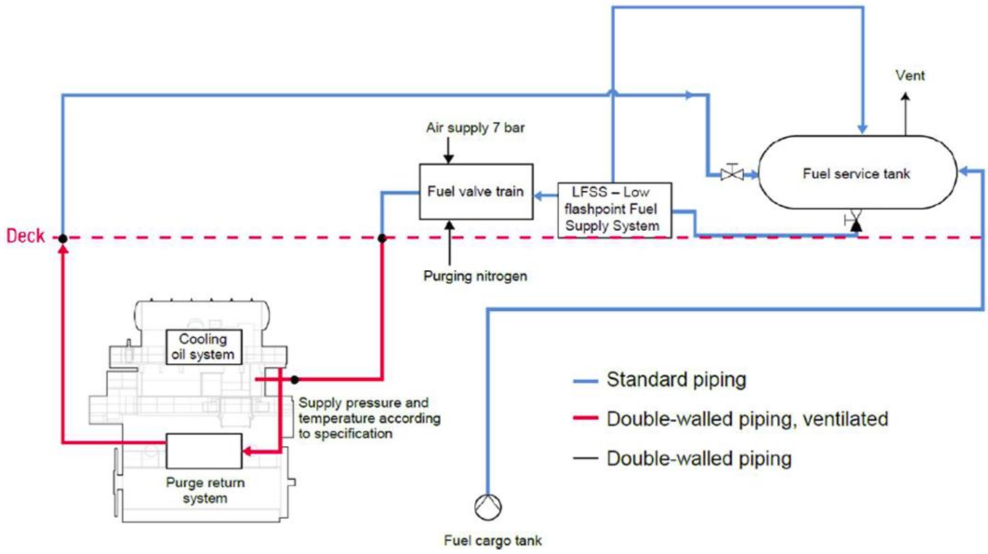


Figure 21. SDF Methanol fuel system simplified P&ID scheme

The performances claimed by Wärtsilä for the use of DF ICE fuelled with Methanol report a reduced NOx and PM production, reduced exhaust temperature and the same or better efficiency. For what concern the IMO ECA emissions, Table 16 report a summary of the measured emission of ICE fuelled with Methanol (39).

	NOx	SOx	PM	CO2
MeOh	30-50%	90-97%	90%	10%
*Compared to the Tier II engine operating on HFO, conventional fuel valve and HFO pilot oil				

Table 16. LNG compared emission reduction, compared to the Tier II engine operating on HFO

The storage system analysis didn't refer to a particular system nor to a real application since no data have been found. Indeed the storage performances of Table 15 of the system have been evaluated taking into account various data from different sources. An approximation has been made on the tank filling coefficient, considered equal to 90%. Another important approximation regards the BoP weight and volume. Both have been considered equal to 10% of the tank weight and the external volume respectively. This value has been extrapolated from the BoP weight and volume of the LNG system.

S6-Compressed Hydrogen

S6 - CH2								
Type	**Pressure**	**Temperature**	**Hydrogen**	**Energy**		**tot Weight**	**Int Volume**	**tot Volume**
-	**bar**	**°C**	**kg**	**MJ – LHV**	**kWh – LHV**	**kg**	**l**	**l**
B	250	20	8	967.8	268.8	382.5	450.0	1,082.5
G	500	20	16.5	1,996.0	554.4	730.6	530.0	1,274.9
L	700	20	3.1	375.0	104.2	143.7	76.0	182.8
X	700	20	25	3,024.3	840.1	1,158.6	612.9	1,474.3
TITAN4	250	20	617	74,638.5	20,732.9	29,500.0	34,000.0	81,785.2
Type	**ED**	**SE**	**Type**	**ED**	**SE**			
-	**kWh/l**	**kWh/kg**	-	**kWh/l**	**kWh/kg**			
B	0.42	1.64	250 bar	0.25	0.70	CH2 volume and weight (BoP and container)		
G	0.68	1.98		0.61	33.60	CH2 volume and weight		
L	0.65	1.77		-	-	with respect to the storage room		
X	0.65	1.77	700 bar	0.57	0.73	CH2 volume and weight (BoP and container)		
TITAN4	0.25	0.70		1.37	33.60	CH2 volume and weight		
				-	-	with respect to the storage room		

Table 17. CH2 storage system performance

Note: CH2 has been evaluated for two pressure values, 250 and 700 (bar). Only systems by Hexagon have been analysed.

- *tot Weight: The BoP weight has been estimated from the TITAN4 system, for similar containerized solution is equal to 27 (kg/kg H2). The total weight of the system was evaluated considering the datasheet tank weight plus the BoP weight.*
- *tot Volume: The BoP volume has been estimated from the TITAN4 system, for similar containerized. Total volume considers the datasheet external tank volume plus the BoP volume.*
- *ED (kWh/l) tank: The value has been evaluated as the ratio between the energy content (kWh) and the tank external volume.*
- *SE (kWh/kg) tank: The value has been evaluated as the ratio between the energy content (kWh) and the tank weight.*
- *250@ED (kWh/l) with BoP: The value has been evaluated as the ratio between the energy content (kWh) and the tot volume of the TITAN 4 system.*
- *250@SE (kWh/kg) with BoP: The value has been evaluated as the ratio between the energy content (kWh) and the TITAN 4 system tot weight.*
- *250@ED (kWh/l) CH2: The value has been evaluated as the ratio between the energy content (kWh) and the internal volume of the TITAN 4 system.*
- *250@SE (kWh/kg) CH2: The value has been evaluated as the ratio between the energy content (kWh) and the H2 weight of the TITAN 4 system.*
- *700@ED (kWh/l) with BoP: The value has been evaluated as the ratio between the energy content (kWh)*

and the tot volume of the X system.

- *<u>700@SE (kWh/kg) with BoP</u>: The value has been evaluated as the ratio between the energy content (kWh) and the X system tot weight.*
- *<u>700@ED (kWh/l) CH2</u>: The value has been evaluated as the ratio between the energy content (kWh) and the internal volume of the X system.*
- *<u>700@SE (kWh/kg) CH2</u>: The value has been evaluated as the ratio between the energy content (kWh) and the H2 weight of the X system.*
- *<u>ED (kWh/l) room</u>: No room has been evaluated for H2 storage.*
- *<u>SE (kWh/kg) room</u>: No room has been evaluated for H2 storage.*

High pressure hydrogen storage system is considered the most mature hydrogen technology among the considered ones and in general. Due to the extremely low density, Hydrogen Energy Density is low. To comply with this, high pressure hydrogen is used as medium. Typical 200 bar standards have been considered too poor by the automotive sector so that two new standards have been established, 350 and 700 (bar). The extremely high pressure required the development of new high pressure vessels, mainly composed by carbon fiber. Different types of storage systems are available based on their construction (47):

- Type I: All-metal construction, generally steel
- Type II: Mostly steel or aluminum with a glass-fiber composite overwrap in the hoop direction
- Type III: Metal liner with full composite overwrap, generally aluminum, with a carbon fibre composite
- Type IV: An all-composite construction featuring a polymer (typically high-density polyethylene, or HDPE) liner with carbon fiber or hybrid carbon/glass fibre composite

Recent CH2 storage systems are based on Type III and Type IV systems. Table 18 (48) shows the energy cost for hydrogen compression. The corresponding costs of production and liquefaction of LNG, LPG and Methanol have not been considered because are fossil fuels. Hydrogen, since is a energy vector produced by primary energy sources is considered different because it could be used to reduce the carbon dioxide production if sustainable energy sources are considered.

Medium	kWh/kg	Note
LH2	12	Existing medium scale
CH2@350	3.1	Average Compression Energy from On-site Production H2
CH2@700	3.2	H2A Projection for Compression and Cooling from 25°C to -40°C

Table 18. Hydrogen conditioning energy costs

As it will results from the study conclusion, Hydrogen is the only energy carrier that could be considered as real alternative solution to decarbonisation, only if the global context is considered. The study though focused on the ships applications for this reason other considerations on the hydrogen cycles have not been analysed.

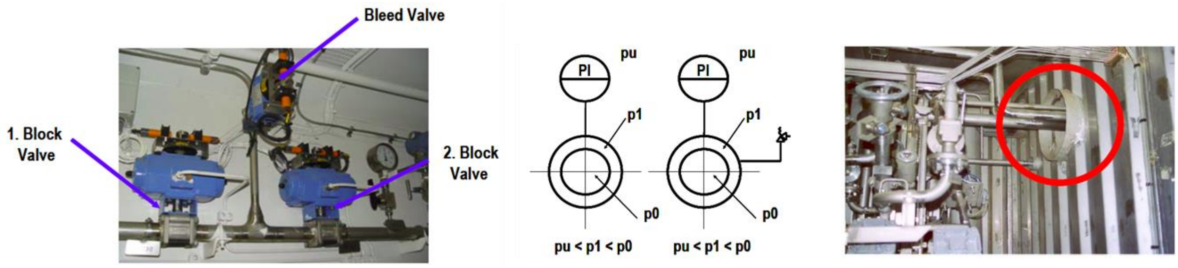


Figure 22. Double block, bleed valve, double walled pipes and ventilated duct examples

From the storage point of view, the energy spent during the compression will result in a fast charging hydrogen medium that don't require complex BoP auxiliary systems. Indeed only pressure regulators are required to control the hydrogen flow. However other BoP requirements connected with the safety aspect have to be considered: double walled pipes or duct ventilated pipes, double block and bleed valves (Figure 22). The Zemship project (49) represents the most important marine example of CH2 installation. Figure 23 shows the installation scheme of the fuel cell power systems and of the CH2 storage system. The project has been developed in accordance with the Germanischer Lloyds fuel cell systems guidelines. The CH2 storage system of the Alsterwasse boat made use of 12 350 (bar) composite tanks for a total storage of 50 kg of hydrogen. Ships application though will require large amount of hydrogen.

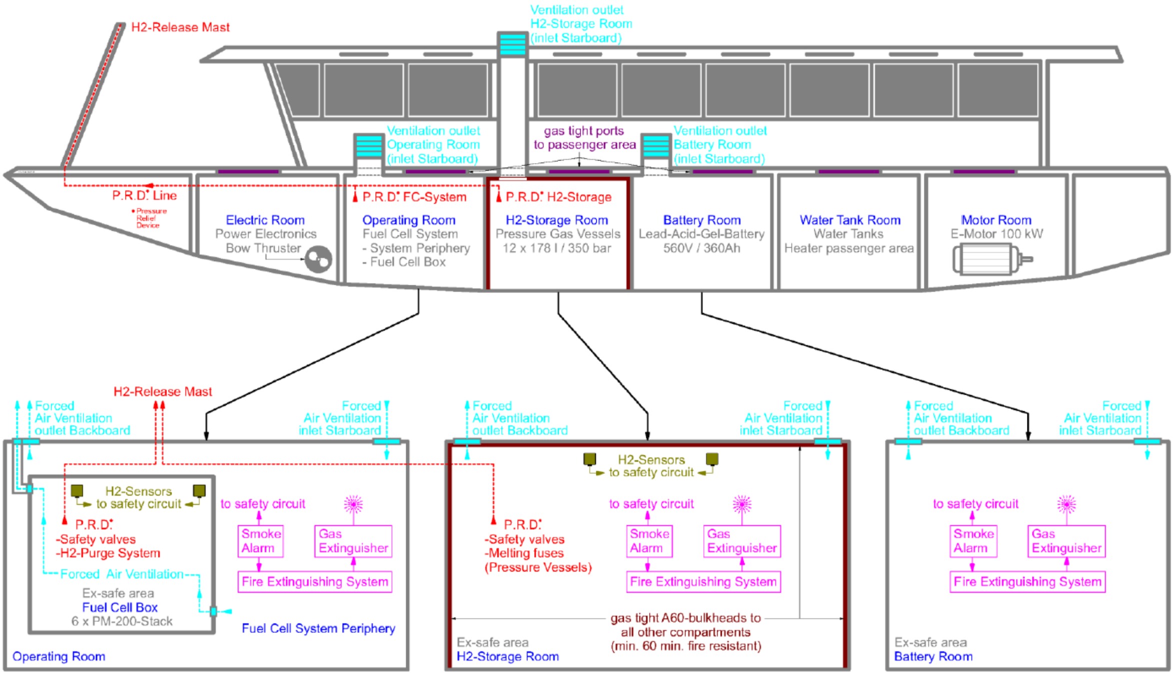


Figure 23. Zemship project. Fuel Cell System simplified P&ID

In order to reach MWh energy storages larger tanks should be considered. From the market analysis only Hexagon products have been found. Large tanks are produced to transport large quantities of gases, natural gas or hydrogen. TITAN4 system of Hexagon (50) represent the right example of a large CH2 storage system feasible for marine applications. Another characteristic of the TITAN4 system that has been considered important is the container modular solution, Figure 24. Fuel cell systems are though to be a potential solution as APU system for ECA zones, for this reason the possibility to install the system on-board already existing ships as well as for the simplification of the storage design has been considered relevant. It has been chosen to compare the performance of other CH2 storage tanks considering the same weight and volume of the TITAN4 BoP, manly represented by the supporting structure.

Table 17 reports the results of the CH2 system analysis. Two pressure levels have been considered, 250 and 700 (bar). The first pressure level is the same adopted for the TITAN4 system. In order to derive the relationship between the tank weight and volume and the BoP other smaller tanks of Hexagon have been considered in the study, with the hypothesis that are all built with the same technique. With the comparative performance analysis it has been possible to derive the hypothetical performance of a similar system based on 700 (bar) pressure level.

Figure 24. Exagon TITAN4 250 bar hydrogen storage

S7-Liquid Hydrogen

S7 - LH2								
Type	Pressure	Temperature	Hydrogen	Energy		tot Weight	Int Volume	tot Volume
-	bar	°C	kg	MJ – LHV	kWh – LHV	kg	l	l
BMW	5	-250	8	959.7	266.6	242.9	143.0	200.0
GM	5	-250	5.4	647.8	179.9	85.0	125.6	154.3
EIHP	5	-250	12	1,439.5	399.9	313.3	214.0	300.0
BMW2	5	-250	12	1,439.5	399.9	189.4	214.0	300.0
Type	ED	SE	Type	ED	SE			
-	kWh/l	kWh/kg	-	kWh/l	kWh/kg			
BMW	1.33	1.1	BMW2	1.33	2.1	LH2 volume and weight (with BoP)		
GM	1.17	2.1		1.87	33.3	LH2 volume and weight		
EIHP	1.33	1.3		-	-	with respect to the storage room		
BMW2	1.33	2.11						

Table 19. LH2 storage system performance

The assessment considered four LH2 tanks, two of which have been designed by BMW automotive company, one from General Motors (GM) and one was the result of the European Integrated Hydrogen Project (EIHP).

Note:

- *<u>tot Weight</u>: The BoP weight has been defined for each system from the available data. The tot weight considers the weight of the tank and of the BoP.*
- *<u>tot Volume</u>: The BoP volume has been defined for each system from the available data. The tot volume considers the vomume of the tank and of the BoP.*
- *<u>ED (kWh/l) tank</u>: The value has been evaluated as the ratio between the energy content (kWh) and the tank external volume.*
- *<u>SE (kWh/kg) tank</u>: The value has been evaluated as the ratio between the energy content (kWh) and the tank weight of the tank.*
- *<u>ED (kWh/l) with BoP</u>: The value has been evaluated as the ratio between the energy content (kWh) and the tot volume of the BMW2 system.*
- *<u>SE (kWh/kg) with BoP</u>: The value has been evaluated as the ratio between the energy content (kWh) and the BMW2 system tot weight.*
- *<u>ED (kWh/l) LH2</u>: The value has been evaluated as the ratio between the energy content (kWh) and the internal volume of the BMW2 system.*

- *SE (kWh/kg) LH2: The value has been evaluated as the ratio between the energy content (kWh) and the H2 weight of the BMW2 system.*
- *ED (kWh/l) room: No room has been evaluated for LH2 storage.*
- *SE (kWh/kg) room: No room has been evaluated for LH2 storage.*

Liquid Hydrogen is considered to be the only medium able to be used on-board ships for large energy storages (51). Container vessels fuelled by liquid hydrogen and powered by fuel cell have already been designed (52). Unfortunately, the Energy Density of LH2 is very poor and the LH2 storage system consequently has poorer performance. The reason why liquid hydrogen is considered the favourite hydrogen storage medium for marine application comes from the highest energy density among the hydrogen medium and fast refuelling. Indeed LH2 is somewhat similar to LNG, even if the temperature at which is stored is very low (-250 against -160 °C). The related problem of refuelling and heating of the cryogenic liquid can be considered similar as well as the Boil-Off problem and the safety hazards related to possible leakage on the steel ship structure. However, LH2, can be thought as a medium-long term solution for large storage system similar to the LNG ones. Indeed if LH2 is substitute inside the Wärtsilä LNG pac, considering the same external dimension and BoP, only 38% of the original energy can be stored. Higher fuel cell efficiency could raise the total system performance but since it is considered a medium-long term solution, it seams likely the use of LNG with Solid Oxide Fuel CEll. SOFC could really represent an alternative thanks to their high efficiency especially if the TG (Gas Turbine) hybrid systems are considered (53). For this reason, LH2 has been considered for smaller energy storages to fuel APU systems or small ships. The choice is supported also by the liquefaction energy cost (54), reported in Table 18.

The system analysis considered small tanks designed for automotive technology because no other data has been found regarding portable large LH2 systems. The assessment shows an improvement in the reliability and energy density of the tanks in particular of the BMW system design, that has been considered as a storage reference. Figure 25, Figure 26, Figure 27 show three of the four system that have been considered during the assessment. System performances has been compared with data collected by (55) and (56).

kWh	**kgH2**
179.9	5.4
m3	**kgH2**
0.126	8.9
tot kg	**tot l**
35	135
15.4	%wt

Figure 25. General Motors LH2 tank prototype

kWh	**kgH2**
270.0	8.0
m3	**kgH2**
0.143	10.1
tot kg	**tot l**
100	200.9
8.0	%wt

Figure 26. BMW LH2 tank prototype #1

kWh	kgH2
403.2	12
m3	**kgH2**
0.214	15.1
tot kg	**tot l**
78	300
15.4	%wt

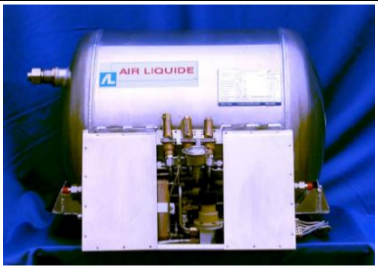


Figure 27.BMW LH2 tank prototype #2

Table 19 report the analysis results. Almost complete information has been found on the internal, external and overall volume as well as the tank and BoP weight (57). At the end of the analysis the performance of the BMW2 tank has been considered as a reference, also on the base of complementary information.

S8-Cryo/Compressed Hydrogen

Cryo-Compressed Hydrogen storages, CCH2, are under development by the same industry that are working on LH2 storage (58). The goal is to have a LH2 tank able to withstand high pressures comes from the present liquid hydrogen storage limitation in terms of: Boil-Off, supply of LH2 (lack of infrastructure), possibility to use CH2. These requirements respond to a particular automotive need, related to fuel flexibility due to the increasing presence of car CH2 refuelling station at 350 and 700 (bar) and the lack of LH2 equivalent. For this reason this system has been assessed but discarded from the analysis because was not considered of interest for ship applications.

S9-Metal Hydrides

S9 - MH2								
Type	**Pressure**	**Temperature**	**Hydrogen**	**Energy**		**tot Weight**	**Int Volume**	**tot Volume**
-	**bar**	**°C**	**kg**	**MJ – LHV**	**kWh – LHV**	**kg**	**l**	**l**
LAB	10	20	3.116	373.79536	103.8321275	420.0	72.2	91.2
ZOZ	10	20	3.116	373.79536	103.8321275	420.0	72.2	91.2
U212	80	20	63	7557.48	2099.301679	4725.0	820	1040.6
Linde	-	20	5.45	654.3272727	181.7577212	630.0	116.9108911	148.4
Type	**ED**	**SE**	**Type**	**ED**	**SE**			
-	**kWh/l**	**kWh/kg**	**-**	**kWh/l**	**kWh/kg**			
LAB	1.20	0.26	AVG	1.58	0.33	MH2 volume and weight (with BoP)		
ZOZ	1.20	0.26		2.00	0.69	MH2 volume and weight		
U212	2.12	0.47		-	-	with respect to the storage room		
Linde	1.29	0.30						

Figure 28. MH2 storage system performance

Note: Strong difference are present between MH storage systems. The systems differ from the metal hydride powder chemical typology and tank design and thermal management. The analysis considered MH system designed for marine application, low temperature and low pressure.

- *tot Weight: The BoP weight has been defined for each system from the available data. The tot weight consider the weight of the tank and of the BoP.*
- *tot Volume: The BoP volume has been defined for each system from the available data. The tot volume consider the vomume of the tank and of the BoP.*
- *ED (kWh/l) tank: The value has been evaluated as the ratio between the energy content (kWh) and the tank external volume.*
- *SE (kWh/kg) tank: The value has been evaluated as the ratio between the energy content (kWh) and the tank weight of the tank.*
- *ED (kWh/l) with BoP: The value has been found as an average of the ratio between the energy content*

(kWh) and the tot volume of the evaluated systems.

- *<u>SE (kWh/kg) with BoP</u>: The value has been found as an average of the ratio between the energy content (kWh) and the tot weight of the evaluated systems.*
- *<u>ED (kWh/l) LH2</u>: The value has been found as an average of the ratio between the energy content (kWh) and the internal tank volume of the evaluated systems.*
- *<u>SE (kWh/kg) LH2</u>: The value has been found as an average of the ratio between the energy content (kWh) and the tank weight of the evaluated systems.*
- *<u>ED (kWh/l) room</u>: No room has been evaluated for LH2 storage.*
- *<u>SE (kWh/kg) room</u>: No room has been evaluated for LH2 storage.*

Metal Hydrides are metal powders able to store hydrogen molecules inside the metal interstice and to keep them stored also at Normal Temperature and Pressure (NTP). The most important characteristic of MH2 systems is the capacity to store hydrogen with high Energy Density, up to and higher that LH2. But what make these systems particular, is that they are able to reach this performances at NTP. Two kinds of hydrides are present, metal hydrides and complex hydrides. The first have been largely studied and developed (59) while the second are under development. The present study considered only metal hydrides. The former has been the object of the studies conducted for the installation of MH2 systems on-board sailboats (60).

The reason why MH2 systems are not considered as the ideal hydrogen storage systems comes from the low Specific Energy. Since are made of metallic compound, the weigh result to be high, for this reason this system has been discarded from the automotive sector. But particular marine application could be suitable to their use. Indeed the most famous and successful hydrogen system application make use of MH2 storage, with a large energy storage (more than 1000 kgH2), the U212 submarine of the Italian and German Navy. Figure 29 shows the installation of the 5 (m) long MH2 tanks on-board the submarine designed by HDW.

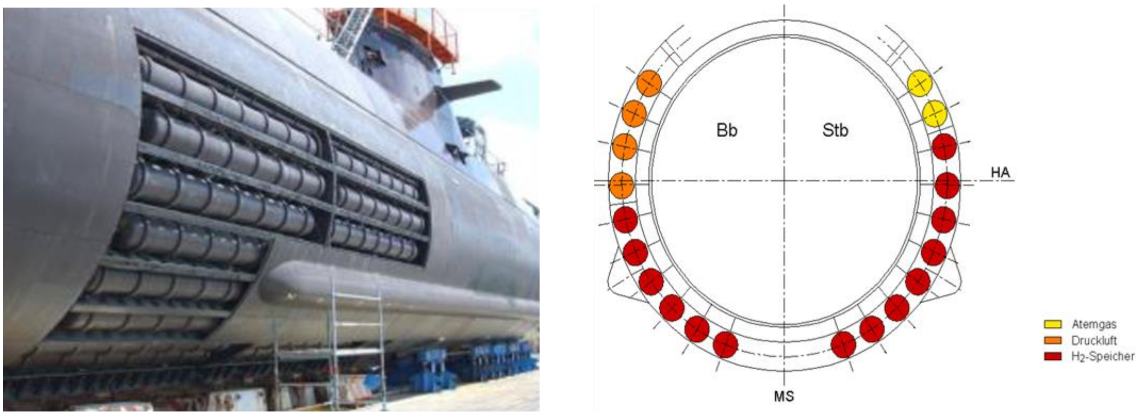


Figure 29.HDW U212 MH2 storage system

Nowadays, several families of intermetallic compounds are interesting for hydrogen storage. Generally, all of them consist of an element with a high hydrogen affinity, element A, and a low affinity one, element B, hence the compound is usually indicated as AB_x. The first element is usually a rare earth or alkaline earth metal which have one electron in their outer layer. As a result, it is very reactive and tends to create a stable hydride. Some examples of these elements are Be, Mg, Ca, Sr, Ba, Ra. Element B is often a transition metal (Sc, Ti, Mn, Fe, Co, Cr, etc.) and form unstable products. Some well defined ratios of B to A in the intermetallic compound have been found to be x = 0.5, 1, 2, 5. In Table 20 (59) the most important families of hydride-forming intermetallic compounds are indicated with their chemical structure, some examples of compounds they form and the respective hydride.

Type	Intermetallic compound	Hydride	Structure
AB_5	$LaNi_5$	$LaNiH_6$	Haucke phases, hexagonal
AB_2	ZrV_2, $ZrMn_2$, $TiMn_2$	$ZrV_2H_{5.5}$	Laves phase, hexagonal or cubic
AB_3	$CeNi_3$, YFe_3	$CeNi_3H_4$	Hexagonal, $PuNi_3$-typ
A_2B_7	Y_2Ni_7, Th_2Fe_7	$Y_2Ni_7H_3$	Hexagonal, Ce_2Ni_7-typ
A_6B_{23}	Ho_6Fe_{23}	$Ho_6Fe_{23}H_{12}$	Cubic, Th_6Mn_{23}-typ
AB	TiFe, ZrNi	$TiFeH_2$	Cubic, CsCl- or CrB-typ
A_2B	Mg_2Ni, Ti_2Ni	Mg_2NiH_4	Cubic, $MoSi_2$- or Ti_2Ni-typ

Table 20. The most important families of hydride-forming intermetallic compounds

The selection of the storage technology and material is greatly dependent on the applicable operating temperature and pressure ranges for the desired application. In this choice, Van't Hoff plot play a paramount role in the design of metal hydride integrated devices. Figure 30 presents Van't Hoff plot for most common hydrides.

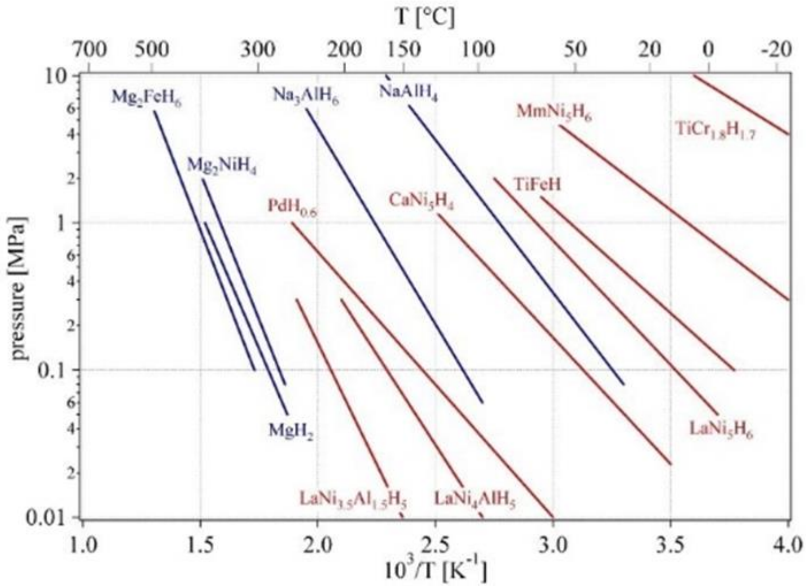


Figure 30. Van't Hoff plot for most common hydrides

Table 28 report has been constructed considering the performance of four different MH2 systems. Indeed different Metal Hydrides are available depending on the metal powder composition. AB_2 and AB_5 MH2 system has been analysed. For the purpose of the comparative analysis the functioning description is not of interest, but it has been developed in Chapter 3.2.

2.1.2 Comparative analysis between energy medium

#		S1	S3	S4	S5	S6	S7	S9
MEDIUM		FO	LNG	LPG	METHANOL	CH2	LH2	MH
STORAGE		Bare Tank	Cryogenic	Pressurized	Bare Tank	Compressed	Criogenic	Bare Tank
note			2 bara	18 bara(1bara)		700 bar	- 252 °C	Intermetallic

MEDIUM	unit	FO	LNG	LPG	METHANOL	CH2	LH2	MH
Density	kg/m^3		450	580.0	792	40.8	70.8	30-60
Energy Density	kWh/l	10.88	5.63	7.47	4.38	1.37	2.38	2.00
Specific Energy	kWh/kg	11.33	13.89	12.88	5.54	33.60	33.32	0.69
P	bar	5-9 (16)	Room	24	Room	690	Room	Room
T	°C	Room-98	-160	Room	Room	Room	-252	Room
Cost	$/kWh	0.05	0.05	0.04	0.08	0.17	0.24	0.17

Table 21. Energy medium comparative table

Table 21 shows the main results of the energy medium data assessment. Among all, the Energy Density and the Specific Energy, evaluated for each medium during the assessment, are reported. These values are of interest in order to define the maximum theoretical performances of the associated storage system (impossible to be reached because the storage system, even if ideal, occupy some space and have a proper weight). Among the most important characteristic of a energy medium there are:

- Density
- Energy Density
- Specific Energy
- Pressure
- Temperature
- Cost

The first two factors determine the capacity of the medium to store energy while temperature and pressure define the physical condition at which the storage system has to operate. Costs in the end will be the main driver that will push towards the adoption of a specific fuel instead of another. The Cost values are just indicative because evaluated on the base of insufficient data. Other consideration are to be made on the energy medium characteristic: NTP state, medium state, toxicity and others. This and other characteristics are reported in Table 22 in order to complete the general assessment given in Table 21. These data have been developed in the comparison model, in which an evaluation of each characteristic is given.

Characteristic	LNG	LPG	METHANOL	CH2	LH2	MH
NTP state	GAS	GAS	LIQUID	GAS	GAS	SOLID
MEDIUM state	LIQUID	LIQUID	LIQUID	GAS	LIQUID	SOLID
TEMPERATURE	CRYO	NO/CRYO	NO	NO	CRYO	NO
PRESSURE	NO	MEDIUM	NO	HIGH	NO	NO
TOXICITY	NO	NO	TOXIC	NO	NO	NO
OTHER		GAS densier than air		embritlement	embritlement	embritlement

Table 22. Energy medium characteristics

From Table 21 some consideration could be made:

- Liquid fuels at NTP are of course favourite with respect to the others. Methanol in this case is the only alternative fuel having this characteristic.

- Low temperature result in cryogenic systems and risks connected with cryogenic liquid leakage that have serious consequences on the iron ship structure resistance in case of contact. For this reason special provision are to be taken in case of cryogenic storage.
- High pressure though are not less problematic from the storage point of view. High pressure vessel are required. Steel based systems result to be too heavy while composite systems are not accepted by IMO and flag administration presently also because of the presence of carbon fibre that is a flammable material.
- Toxicity is an issue. All the assessed alternative fuel are asphyxiating in the gas state, flammable and explosive over different ranges. Only Methanol though is toxic. This represent a main drawback because it will require special safety measures that will result in more complex, voluminous and heavier BoP.
- Other safety concern characteristics are hydrogen embritlement and gas density with respect to air density. The first is peculiar of hydrogen systems and require the use of high costly material like 316 L steel. The second require dedicated ventilation system, that would require different design approach from the other gases. The same would apply for the use of oxygen in the case.

From the analysis, an important observation was derived:

"LNG, LPG and Methanol are able to fulfil IMO emissions limitation if directly used inside ICEs"

Indeed the use of these alternative fuel permits the compliance of the Sulphur limitation when burned inside ICEs but the reduction of NOx emission is not always sufficient to comply with Tier III limitation in NECA areas, requiring the use of EGR or SCR systems on the ICE.

For reasons that will be explained during the conclusion of the study, it has been chosen to compare large energy storage systems, with similar storage capacity for LNG, LPG and Methanol. From the energy medium analysis these fuels have been considered different from hydrogen since are able to work with ICEs as observed above. Hydrogen energy medium though, CH2, LH2 and MH have been analysed in conjunction with smaller high modular storage systems (containerized solutions) where possible.

2.1.3 Comparative analysis of energy vectors storage systems

#		S1	S3	S4	S5	S6	S7	S9
MEDIUM		FO	LNG	LPG	METHANOL	CH2	LH2	MH
STORAGE		Bare Tank	Cryogenic	Pressurized	Bare Tank	Compressed	Criogenic	Bare Tank
note			2 bara	18 bara(1bara)		700 bar	- 252 °C	Intermetallic
STORAGE	unit	Bare Tank	Cryogenic	Pressurized	Bare Tank	Compressed	Criogenic	Bare Tank
Energy Density	kWh/l	10.55	3.70	4.01	3.62	0.57	1.33	1.58
Specific Energy	kWh/kg	10.99	6.30	7.03	5.03	0.73	2.11	0.33
CO2 Factor	$kgCO_2/kWh$	0.27	0.18	0.22	0.25	0.00	0.00	0.00
Cost	$/kWh	-	0.94	1.95	2.18	28.5	30.2	332.5
High production	$/kWh					2-4.4	8-15.2	
note			Type C tank	IMO5-container		container sol	liquefaction	30 bar

Table 23. Energy medium Storage Systems comparative table

Table 23 shows the results of the energy vector storage system performances. In the following some observation are given:

- Generally the energy medium storage capacity is never reached by the storage systems. Indeed a large difference between the energy vector performance and the storage performance has been found, in particular for the alternative energy vectors. The reason lay on the necessity to maintain extreme conditions of low temperature and pressures. FO and Methanol are the storage systems that present the minimum impact in terms of volume and weight of the storage system together with Metal Hydrides. These system result to be favoured by the capacity to perform at NTP.

- Large differences have been found between LNG, GPL and Methanol storage systems and Hydrogen storage systems (CH2, LH2 and MH2). This confirm the trend that was found during the analysis of the energy vectors, meaning that hydrogen storage systems are not able to influence significantly the poor energy density performance of hydrogen as energy vector.
- When considered for fuel cell applications, the following combinations have been found preferable:
  1. LNG and SOFC
  2. Methanol and HTPEMFC
  3. Hydrogen and PEMFC

  An important consideration should be made on the second configuration. The use of Methanol inside the analysed MeOH reformer require a fuel mix with 60% vol of distillate water. Has was showed by the fuel cell SOA (Chapter 2.4.1), the reaction water is not sufficient to the reaction so that a storage of distilled water is required. If 50% vol of water is supposed to be required, the consequences on the energy vector Energy Density bring to a half capacity, even worse for the Specific Energy. In this case LH2 become competitive considering the higher PEMFC efficiency.
- Even if the available data are not sufficient to derive confident information on costs, the cost analysis on the energy vector and storage system has been done. The analysis show the low cost of LNG against the other fossil fuel based energy vectors (LPG and Methanol) and a substantial difference between LH2 and CH2 that favour the second. When the storage systems cost are analysed, Hydrogen storage systems become out of market. Only considering high production rates these storage system costs could be competitive but still at a higher costs with respect to other solutions.
- Finally, the CO_2 factor has been considered. Although it is related to the energy medium rather that to the energy medium storage, it has been considered in Table 23 because the former represent the final output to be considered from the analysis. Moreover, CO_2 factor could represent the only technical driver able to rise the shipping interest into the use of hydrogen rather than fossil fuels. That is because as it has been proven by the assessment, LNG, LPG and Methanol are already able to fulfil IMO emission requirements even with ICE. Only the consideration of GHG production from ships will make the CO_2 factor significant. In that case, Hydrogen is the only energy vector able to significantly reduce the CO_2 production.

2.2 Comparative models

The decision to build a comparison model to study the differences between the fuel cells technology in order to better understand their capabilities and limitations, rises from the following consideration: it's difficult to compare different technology when there are so many factors related one to another and each of them could be an advantage or a disadvantage as the case.

This was the motivation that drove the construction of the first comparison model published on the bachelor thesis in 2012 (61). The model was used to identify the most suitable fuel cell technology for marine application and the most suitable hydrogen storage technology. But the same comparative model has been constructed and used by DNV-GL for the "STUDY ON THE USE OF FUEL CELLS IN SHIPPING" commissioned by EMSA and published in early 2017 (63). Figure 31 shows the model results of the DNV-GL. The output results from this model were the same of the comparative model published in 2012. The most fuel cell suitable technologies for marine applications are: PEMFC, HTPEMFC and SOFC.

The DNV-GL study provides useful information on fuel cell technologies, standards and regulation guidelines and a detailed risk analysis for the adoption of fuel cells on-board a Ro-Ro ferry. What the study doesn't give is the evaluation of fuel cell performances and more important the fuel storage system analysis. Indeed the following PhD thesis try to respond to these two important aspects. From the fuel cell performance analysis (Chapter 2.4.1) it resulted that fuel cells are able to compete with other generator technologies, while fuel cell energy vectors storage system represents the real obstacles. For this reason the analysis of this aspect is considered of importance.

The comparison model could be considered as a spatial model in which the goodness of the evaluated system is derived by the distance from the ideal condition. Through a system of points, the ideal condition is represented by the maximum evaluations so that the better choice is the one with more points. The comparison models have been designed with two parts. The first one is the evaluation model that considers a general comparisons between the technologies, without consider the particular characteristics required from the application. The second one, try to considers these characteristics by the use of a multiply factor called factor x or weighting facto. The analysis of the models, the way the characteristics and the factors of judgment have been chosen, all contribute to the study in order to understand which system better suits our requirements.

Essentially, all models are wrong but some are useful.

George E.P.Box

Technology / Attributes	Relative cost	Module kW levels	Lifetime	Tolerance for cycling	Fuel	Maturity	Size	Sensitivity fuel im-purities	Emissions	Safety Aspects	Efficiency	Total
Weighting	3	2	3	2	3	3	3	3	2	3	3	
Alkaline fuel cell	3	3	2	3	1	2	2	1	3	3	2	
	9	6	6	6	3	6	6	3	6	9	6	66
Phosphoric acid fuel cell	2	3	3	2	2	2	1	2	3	2	2	
	6	6	9	4	6	6	3	6	6	6	6	64
Molten carbonate fuel cell	1	3	3	1	3	3	1	3	1	2	3	
	3	6	9	2	9	9	3	9	2	6	9	67
Solid oxide fuel cell	1	3	2	1	3	3	2	3	2	2	3	
	3	6	6	2	9	9	6	9	4	6	9	69
Proton Exchange Mem-brane	3	3	2	3	1	3	3	2	3	3	2	
	9	6	6	6	3	9	9	6	6	9	6	75
High Temperature PEM	2	2	2	3	2	2	3	3	3	2	3	
	6	4	6	6	6	6	9	9	6	6	9	73
Direct methanol fuel cell	2	1	2	3	3	1	2	3	1	3	1	
	6	2	6	6	9	3	6	9	2	9	3	61

Weighting use the scale 1 to 3, with 3 indicating the highest in importance
Ranking use the scale 1 to 3, with 3 indicating the highest character
A high total score is indicating high attractiveness

Figure 31. EMSA-DNV-GL fuel cell comparative model

The comparative models have to be considered as instruments to help the choice of the right alternative solution to FO and ICE. Indeed the identification of the most technical and economical solution become very complex due to the missing “silver bullet” solution. Until today, no alternative technology or alternative fuel was able to compete with the ICE and FO duo. Neither in terms of technical or economical performance. The new “environmental” drivers though, are penalizing the use of FO permitting the introduction of new alternative fuels into the market, all different between them, all able to supply different generators.

For these reason, the following question has been rise:

How could the “hydrogen technologies” be compared with the “alternative solutions”?

“Hydrogen technologies” are represented by different kinds of fuel cells (PEM, HTPEM, AFC, SOFC, MCFC, DMFC) and different kinds of hydrogen storages (CH2, LH2, MH2) or reformed fuels (Methanol, LNG, LPG, diesel). “Alternative Solutions” are represented by all the alternative possible combination of generators (TG, ICE, TV, Batteries, Other) and alternative fuels (LNG, LPG, LS fuel oil, others).

In order to respond to this difficult question, comparative models have been designed. The goal is the construction of a tool able to elaborate the data collected during the alternative energy vector analysis, with data of generators, reformers and exhaust treatment systems.

In the following, five comparative models referred to the following systems have been designed:

- Fuels

- Storage
- Reformers
- Generators
- Exhaust gas treatment

The models are still under development. They have been designed to assess with a weight factor the most suitable technology for SSS, in particular for Ro-Ro ferries.

2.2.1 Fuel comparative model

In the following the comparison model designed for fuels is presented. “Fuels” are considered as marine fuels, as descripted in Chapter 2.1, it correspond to the definition B of fuel. Indeed marine fuels are energy vectors. In particular the following have been considered:

- HFO – Heavy Fuel Oil
- LSFO – Low Sulphur Fuel Oil
- Propane
- Methanol
- NG – Natural Gas
- Hydrogen

The considered model characteristics are the most important design parameters that characterize the model. A deep analysis of the relation between the chosen characteristics of the fuel comparative model and the relation of the fuel model characteristics and the other model was not done because the study is not complete already. But four main characteristic groups have been found among all the characteristics of all the model, that are:

- Performance
- Cost
- Regulation
- Safety

All the designed model have been constructed considering mainly Performance Characteristic because the purpose of the following study is the analysis of the most technical suitable technology. But for the “Fuel Comparison Model” and the “Storage Comparison Model” a more complete analysis is presented.

An evaluation between 0 and 2 has been given to the fuels characteristics, were 0 correspond to the lowest characteristic value and 2 to the higher characteristic value present among the fuels. The weight factor though, has been evaluated between 0 and 1. The general model total result consider the sum of the characteristic points, while the particular model is equal to the sum of the general characteristic point value multiplied to its correspondent weight factor. The following example considered a weight factor for the “Regulation” characteristics, since for SSS application, the main driver is considered to be the rule framework, that operate towards the imposition of emission restrictions, fees, tax. In order to evaluate these aspects, the following factors have been weighted:

    - S content

- CO_2 production
- Fuel cost
- Distribution and Logistic

The model result show that HFO and LSFO remain the most convenient fuels, while LNG and Propane are slightly more convenient than the other alternative fuels. In any case, the study confirm the fact that there is not a “silver bullet” alternative fuel solution. Moreover it has to be considered that a more complete results should consider the result of a set of solutions: fuel, storage, reformer, generator and exhaust treatment.

Characteristic	unit	HFO	Vote (0-2)	LSMFO	Vote (0-2)	PROPANE	Vote (0-2)	METHANOL	Vote (0-2)	NG	Vote (0-2)	HYDROGEN	Vote (0-2)	Factor
ATP	-	liquid	2	liquid	2	gas	1	liquid	2	gas	0	gas	0	1
Energy Density	kWh/l	11.68	2	11.91	2	0.03	0	4.14	1	0.0094	0	0.0029	0	1
Specific Energy	kWh/kg	11.78	2	12.02	2	12.88	2	5.54	1	13.89	2	33.60	2	1
S content	%	3.5	0	0.1	1	0	2	0	2	0	2	0	2	2
CO2 production	kgCO2/kWh	0.27	0	0.27	0	0.22	0	0.25	0	0.18	1	0	2	2
Fuel Cost	$/kWh	0.03	2	0.05	1	0.04	1	0.08	1	0.05	1	0.17	0	2
Fuel Treatment	-	M	1	H	0	M	1	M	1	H	0	H	0	1
Safety	-	F	2	F	2	F; E; X	1	F; E; T	0	F; E	1	F; E	1	1
Legislation	-	E	2	E	2	R	1	R	1	R	1	R/A	1	1
Distribution and Logistic	-	E	2	E	1	R/A	1	R/A	0	R/A	1	A	0	2
General			15		13		10		9		9		8	
Particular			19		16		14		12		14		12	

ATP	LIQUID	GAS		
Energy Density	#			
Specific Energy	#			
S content	#			
CO2 production	#			
Fuel Cost	#			
Fuel Treatment	High	Medium	Low	Difficulty
Safety	# CLASS			
Legislation	Established	Ready	Absent	
Distribution and Logistic	Established	Ready	Absent	

Safety # of class	
E	Explosive
O	Oxidising
F	Flamable
T	Toxic
X	Harmful
C	Corrosive

Table 24. Fuel comparative model table

2.2.2 Storage comparative model

The storage model was designed considering performance and cost characteristics. In order to evaluate the impact of regulation characteristic a rule framework should be present. At the present, the IMO IGF code rule the use of LNG in ICE only. The future amendments of IGF code will permit the evaluation of other fuel storage systems too.

The weight factor has been considered for the following characteristic:

- Medium
- Energy Density
- Specific Energy
- Storage Cost

The model results shows a clear division between fossil fuels and hydrogen storage systems. FO storage system is the most convenient energy storage system, thanks to the high energy density and specific energy of petroleum and the liquid state at NTP conditions, it take advantage of the weight factor within all the chosen factors. Methanol and LPG results to be the best alternative fuel when the storage system characteristics are evaluated. The reason rely on the liquid state of Methanol at NTP and the easy conditions at which LPG could be maintained. LNG instead, is penalized from the storage system point of view as are the hydrogen storage systems that summed an average total score that is less than a third of the FO one.

Characteristic	unit	FO	Vote (0-2)	LPG	Vote (0-2)	METHANOL	Vote (0-2)	LNG	Vote (0-2)	CH2	Vote (0-2)	LH2	Vote (0-2)	MH	Vote (0-2)	Factor
Medium	-	L	2	L	2	L	2	L	1	G	1	L	1	S	0	2
Type of Tank	-	B	2	P	1	B	2	C	0	P	0	C	0	B	1	1
Energy Density	kWh/l	10.55	2	4.01	1	3.62	1	4.07	1	0.57	0	1.33	1	1.58	1	2
Specific Energy	kWh/kg	10.99	2	7.03	1	5.03	1	6.93	1	0.7	0	2.11	1	0.33	0	2
Fuel Treatment	-	M	1	L	2	M/L	1	H	0	L	2	H	0	L	2	1
Boil off	-	N	2	N	1	N	2	Y	1	N	2	Y	1	N	1	1
Storage Cost	$/kWh	0	2	1.95	2	2.18	2	0.94	2	28.50	0	30.2	0	332.5	0	2
General			13		10		11		6		5		4		5	
Particular			21		16		17		11		6		7		6	

Medium	LIQUID	GAS	SOLID
Type of Tank	BARE	PRESSUR.	CRYOG.
Energy Density	#		
Specific Energy	#		
Heating/Cooling	REQURE	NOT REQ.	
Fuel Treatment	High	Medium	Low
Boil off	YES	NO	
Storage Cost	#		
Fuel Cost	#		

* Service Tank and treatment system, Heating and cooling, Handling

Table 25. Storage comparative model table

2.2.3 Reformer comparative model

The reformer comparative model considered the characteristics of two different reformers: A methane Steam Reformer (SR) designed for land applications and a diesel Autothermal Reformer (ATR) designed for automotive applications. The performance of the methane SR has been assessed as an average between two industrial systems while the diesel ATR characteristics were defined from prototype systems developed before the DOE excluded this technology for automotive applications.

The reformer systems are required to generate hydrogen rich gas that generally, is supplied to a fuel cell. Indeed there's no reason to burn hydrogen in ICE, TG boiler or other. The reason why the process could be considered interesting for ship operators comes from the good performance in terms of efficiency, comfort and power density of fuel cells together with the zero emission characteristic. As a matter of fact, the total efficiency (about 70% reformer and 50% fuel cell) could be of about 30-35%, lower that 40-45% of large ICE that however are able to perform such results only near the MCR. Fuel cells on the contrary have almost constant efficiency with respect to the load, indeed it is higher at partial load. This solution permit the use of higher energy density vectors like FO or LNG reducing operating costs, saving space and weight from the storage and taking advantage of a already present infrastructure. But reformers require large volumes and weight, long start-up time, increased system complexity and lower fuel cell performance so that in the end, this solution result to be levelled with the others.

Some fuel cell technology operate at high temperature so that their coupling result to be favoured, Chapter 2.3.1. Methanol in particular, result to be an attractive solution with HTPEMFC. The former has a high working temperature that could be used inside the methanol SR together with the anode outlet. For this reason the industry is developing integrated module of HTPEMFC with methanol reformer. It is thought that this solution better comply with ships requirements, for this reason the presence of an external methanol reformer for fuel cell was not considered in this example.

The considered weighting factors were:

- Efficiency
- Energy Density
- Specific Energy
- Water consumption

From the comparative model it is possible to state that, even if the characteristics data of diesel ATR are less certain, this reformer unit result to be better than methane SR, mostly because of its external dimensions and weight.

Characteristic	unit	NG-H2	Vote (0-2)	Diesel-H2	Vote (0-2)	Factor
Type	-	SR	1	ATR	2	1
Eta	%	69	2	43	1	2
Power Density	kWH2/m3	1.931	0	40.67	1	2
Specific Power	kWH2/kg	0.011	1	0.037	1	1
Water consump.	kg/kWhH2	4.12	1	0	2	2
Power consump.	kW/kWH2	0.054	1	0	2	1
Fuel factor	%	100	2	75	0	1
General			8		9	
Particular			11		13	

Table 26. Reformer comparative model table

2.2.4 Generators comparative model

The fuel cell comparative model was the first step towards the definition of the most suitable hydrogen technology for marine applications. However, the comparison was made among fuel cells only, while real application have to face other technology too in order to be considered competitive. In the following, a comparative model example is presented with the goal to assess the characteristics of different energy generator technologies. Since many of them are able to work with different fuels, the comparative model should consider the characteristic of a determined generator supplied with a specific fuel. In particular the following combination have been considered:

- ICE+LNG/LPG
- HTPEM+Methanol
- PEM+H2

The reason that rely behind this choice comes from the energy vector analysis and experience. Indeed, future study development will evaluate all the possible combinations because due to the complexity of the whole system, some apparently not convenient solutions can in the end result favourable. Considering the "climate change" challenge and the consequent "Regulatory" driver, with the example it was chosen to show the results of the most feasible short term solution (ICE+LNG/LPG), the most feasible mid term fuel cell solution (HTPEM+Methanol) and the most environmental mid term solution (PEMFC+H2). It is an author belief that the future long term solution will be represented by Hybrid SOFC systems fuelled with LNG or hydrogen. This solution has been left aside for future analysis.

It has been chosen to consider only solutions that already comply with the sulphur IMO requirements, without considering the CO2 factor, because it is considered a medium-long term characteristic while the example wants to focus in the short-medium terms. The considered weighting factors are:

- NOx emissions
- Costs

Again, the example consider a possible Short Sea Shipping (SSS) application. The model results show that in this case, ICE+LNG and PEMFC+H2 are favourite against HTPEM+Methanol. To be effective the comparative model should be used weighting the importance of each characteristic as was done with the weighing factor, but also the importance and relation between the considered characteristics. Moreover the evaluation have to be based on specific criteria that have to be chosen together with the characteristic on the base of the goal of the analysis, as boundary conditions. This example shows why the comparison model should be used as a decision tools rather than a scoring list used to define the winner.

Engine	unit	ICE	Vote (0-2)	PEMFC	Vote (0-2)	HTPEM+REF	Vote (0-2)	Factor
Fuel	-	**LNG-LPG**	**0**	**H2**	**0**	**Methanol**	**0**	**0**
Specific Power	kW/kg	0.07	1	0.29	2	0.07	1	1
Power Density	kW/l	0.06	1	0.24	2	0.06	1	1
ETA (MCR)	%	0.47	2	0.5	2	0.24	0	1
ETA (50%MCR)	%	0.44	1	0.51	2	0.22	1	1
NOx	g/kWh	2.6	0	-	1	-	1	2
Fuel Consumption	g/kWh	185	1	75	1	380	1	1
Air supply system	g/kWh	7600	0	3800	1	11760	0	1
Vibration	-	yes	0	no	1	no	1	1
Electric AUX	-	small	1	small	1	small	1	1
Cost	$/kW	150	2	3000?	0	3000?	0	2
Heat recovery	-	high	2	low	0	medium	1	1
Start-Up time	s	60*10^0	1	1*10^0	1	60*10^0	1	1
SOA	-	ready	2	ready	1	ready	1	1
General			14		15		10	
Particular			16		16		11	

Specific Power	kW/kg		
Power Density	kW/l		
ETA (MCR)	%		
ETA (50%MCR)	%		
NOx	g/kWh		
Fuel Consumption	g/kWh		
Air supply system	g/kWh		
Vibration	-	Yes	No
Electric AUX	-	Small	Medium
Cost	$/kW		
Heat recovery	-	Small	Medium
Start-Up time	s		
SOA	-	Reasy	Not Ready

Table 27. Generators comparative model table

2.2.5 Exhaust treatment comparative model

Exhaust gas treatment are required whenever fuels with high percentage of sulphur are used or ICE or other energy generator producing NOx are used. When alternative fuels are used, scrubber are not necessary. Moreover, many ICE OEMs are able to provide IMO Tier III engines supplied with gas, NG or LPG or Methanol. Anyhow the model has been built and used to the evaluate the final example. The following table present a simple comparative model of the available exhaust gas treatment technologies. The weight and volume data are only approximate because a complete assessment of the entire systems is difficult due to their complexity.

No weight parameters have been evaluated because for the analysed SSS application has been considered mainly with alternative fuels and hydrogen in particular. In any case, the development of the study will consider also the confront between alternative fuel solutions and traditional fuel solutions.

Characteristic	unit	Exhausts	Vote (0-2)	Factor
Scrubber			0	0
Weight	kg/kW	0.275	1	1
Volume	l/kWh	30.36	0	1
Power	% engine	0.5-1%	1	1
NaOH	l/MWh*%S	6	1	1
General			3	
Particular			3	
EGR			0	0
Volume	m3/kW	0.28	1	1
Weight	kg/kWh	0.73	2	1
Power	% engine	1%	0	1
NaOH	l/MWh*%S	1.52	1	1
General			4	
Particular			4	
SCR			0	0
Volume	m3/kW	0.28	1	1
Weight	kg/kWh	3.29	0	1
Power	% engine	1%	1	1
Urea	l/MWh*%S	18.40	2	1
General			4	
Particular			4	

Table 28. Exhaust treatment comparative model table

2.2.6 Results discussion

The process of data analysis and elaboration of Chapter 2.1 resulted to be infertile without a proper data comparison and the assessment of the relations between the various element of the energy system, from the fuel to the exhaust gas emission passing through the fuel storage, the fuel treatment systems and generators. For this reason, the comparative models represent an important analysis tool. The main goal of the comparative models is the evaluation of the boundary conditions on the energy system characteristics in order to help the identifications of technical or economical obstacle and to find the most suitable energy solution able to comply with the context.

The models then, are useful tools that have been used to support the analysis of the energy systems.

This Chapter shows a practical example of the data analysis for the assessment of a energy system for SSS applications, in particular for Ro-Ro ferries. The former has been conducted making use of the maturated experience for the choice of the examined technologies and characteristics, but a complete analysis should take into account all the possible technical solutions. Figure 32 shows the configurations that have been found between the following system components:

- Fuel
- Fuel Storage (energy medium)
- Reformers (fuel treatment)
- Generators
- Exhaust gas treatment

The scheme takes into account also other alternative fuels, storage systems and generators (Byodiesel, CNG, TG, SOFC) that were not considered during the study but that will be developed in the future. It represent the first tentative to draw a design scheme able to consider all the power generation system components, from the fuel to the exhausts. The data analysis will be further developed with comparison models that will take into account all the possibility in order to produce the most complete analysis whenever particular boundary conditions will be set to weight factors. The final goal is the definition of the characteristics (quantitative and qualitative) of every possible solution.

FUEL	LSMFO		PROPANE		METHANOL			NATURAL GAS		HYDROGEN		
STORAGE	FO		LPG		METHANOL			LNG		CH2	LH2	MH2
GENERATOR	ICE	HTPEM	ICE	PEM	ICE	HTPEM	PEM	ICE	PEM	PEM	PEM	PEM
REFORMER	-	DIESEL	-	NG	-	-	NG	-	NG	-	-	-
EX NOX	SCR	-	EGR	-	-	-	-	-	-	-	-	-
EX S	-	-	-	-	-	-	-	-	-	-	-	-
General	61	66	60	59	64	60	59	59	54	58	57	58
Particular	74	82	72	73	75	70	72	71	68	64	65	64

Table 29. Total comparative models analysis results

Indeed Table 29, shows an example of some chosen configurations. It display the total sum of the points collected for each components in the comparison models. When a component like Reformer, Sulphur exhaust gas filters or NOx exhaust gas system are not required, the element score is equal to the maximum score as if 2 points are given to all the characteristics. This way, system requiring one of these elements result to be penalised. The total score gives a qualitative indication of the value of the considered solution in comparison with the others. The value of each single components gives an indication of the weak and strong characteristic of the system. The scheme of Figure 32 will be used also to define quantitative values of kWh/l, kWh/kg, costs, emission and others. Table 68. System performance calculations scheme of Chapter 5 shows the quantitative results that is possible to derive from the comparative study and models descripted.

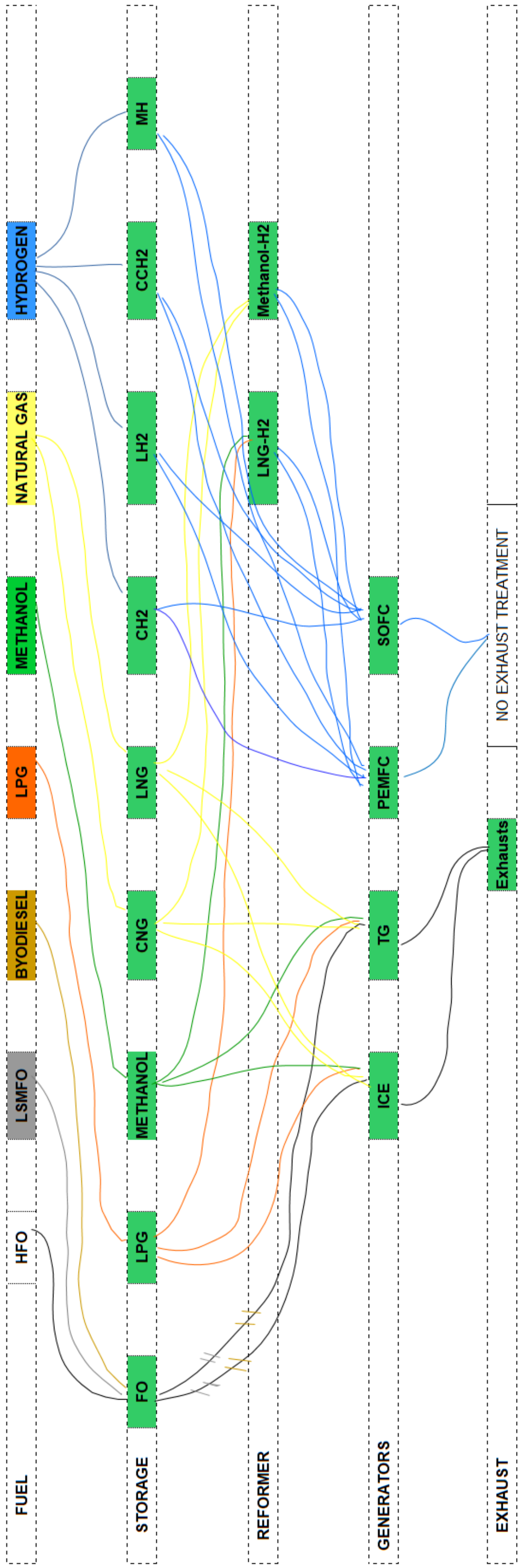


Figure 32. Comparative models configurations

2.3 Fuel Cell State Of the Art (SOA)

2.3.1 Fuel Cell modules

The fuel cell comparative model results (61), supported by DNV study commissioned by EMSA (63), show the PEM fuel cell as one of the most promising fuel cell technology for marine applications together with HTPEM and SOFC. As previously said, SOFC are considered the most suited technology for the medium/long period, while during the short/medium term, the first two technologies are thought to be ready to be installed on-board. The reason comes from the technical analysis made during the comparative study but also from a practical market assessment. Fuel Cells found suitable applications in a number of niche sector that gave them the possibility to be a competitive technology on already established market or that are on the verge to be introduced in it. PAFC have been firstly developed for CHP systems mainly fuelled by methane in Japan to be later replaced by PEMFC with reformers (64), while MCFC results to be an important asset of one of the largest multinational company in South Korea, POSCO, who design and build MW size MCFC power plant (65). Both these examples show how different fuel cell technologies present different characteristics that could be advantageous or disadvantageous depending on the applications.

In the case of ship applications, power density in terms of weight and volume as well as other characteristics like dynamics, temperatures and so on, indicate PEM, instead of PAFC or MCFC as most suitable technology even if the SOA of marine applications don’t show a clear historic trend for their usage. Indeed, PEMFC is the most studied and developed fuel cell technology by another sector, the automotive sector. The former, due to the high rate of production is able to develop new technologies much faster than shipping sector. Market saturation together with the public concern on environmental challenge and health risks connected to transport emissions, are pushing automotive industry to the development of low emission power train. After the remarkable results obtained on diesel and gasoline fuelled internal combustion engines in terms of emission reduction and efficiency, the industry move to the adoption of alternative fuels first (LPG and NG) and the use of hybrid systems later (ICE+Batteries) to comply with always more stringent emission limits. While hybrid cars have been established into the market, industries are starting to introduce full electric vehicles able to further reduce the emission to zero. Batteries (mainly Li-Ion) are developed and integrated inside the vehicles, but in order to completely substitute ICE and fossil fuel two important technical obstacles are to be overcome: range and refuelling time. In order to challenge these problems, almost all worldwide automotive companies are developing fuel cell based power train for their cars. Some are producing their own property technology others rely on third OEMs that are increasing in numbers and available products. In any case, the unique developed technology result to be PEM. Thanks to these important research efforts, this technology became more and more reliable, durable and performing. Alongside fuel cells, MH storage systems have been developed as explained in Chapter 3.2.

The EU Commission and USA DOE support research programs with the goal to develop high TRL products in order to promote the introduction of fuel cells into the market. The FCHJU Private Public Partnership, responsible of the funds dedicated to fuel cell and hydrogen research during the last two EU research program (7th Program and Horizon 2020), contributed to the rise of PEMFC’s TRL for automotive application. Today, PEMFC are considered technical ready to be introduced into the automotive market while the obstacles remain the infrastructure and the large-scale production. The last aspect is pushing the OEMs fuel cell producer to explore new applications for their products, marine applications are considered among the most promising. The number of research projects dedicated to the application of fuel cell on-board ships is increasing (ref DNV) and the observed trend consist in the technology transfer from the automotive to the marine sector.

This short practical market assessment shows why PEMFC will be the main fuel cell technology installed on ships in the short/medium term. For this reason an assessment of the main products available on the market has been done (Table 30). Only the most notorious OEM's companies have been considered, while stacks produced by automotive company have been left out. From the assessment it is possible to notice the presence of a standard size common to almost all the producer, 30 (kW). It is not clear how this standard established and if there's a technical reason for it since last fuel cell powered cars use fuel cell stacks with a power range of about 100 (kW). The former power size is available through the connection of more 30 (kW) stacks as the one produced by Hydrogenics or connecting more modular stacks as made by Ballard with its FCvelocity – 9SSL stack that range from 4 to 20 (kW) power. All the fuel cell producer are able to supply stacks but the trend is the supplier of fuel cell modules, stacks provided with the basic fluid and electric interface required to control the stack. This choice has been made to ease the fuel cell system integration and to guarantee the right control of the stack.

If you consider the power density of the fuel cell stack only, you get very high numbers. One of the highest power density stack is the one provided by Power Cell (Figure 33), with its 3.61 (kW/l) and 3.10 (kW/kg), compete with the stack performance of the brand new Toyota Mirai (3.1 kW/L and 2.0 kW/kg).

Figure 33. Powercell S3-335C FC stacks comparison with Ballard HD60 FC module

However, to be significant the power value should be related to the volume and weight of the stack including the Balance of Plant (BoP) components and connections. The former can be defined as fuel cell module, following the terminology given by IEC/TS 62282-1 international standard. A detailed list of these components has been produced during the analysis of the Fuel Cell System (Chapter 2.4.2). In this phase it is sufficient to understand the difference between the bare fuel cell stack and what is called as the fuel cell module. For the purpose of the thesis, and of the marine application too, the module power density should be considered. Figure 33 shows the visual difference between a stack and a module. The importance of the definition of a standard level of integration for the supply of fuel cell products comes from the ship industry requirements that operates as system integrators. For this reason, it's likely that the integration of fuel cell on-board ships will consider fuel cell modules instead of fuel cell stacks.

Producer	Type	Power	Tension	Current	Iddle Power	PH2	L	W	H	Volume	Weight	Power Density	Specific Power
0	0	kW	V	A	kW	bara	mm	mm	mm	l	kg	kW/l	kW/kg
Ballard	HD60	60	220-350	-	3.3	8	1130	869	506	496.9	244	0.12	0.25
Ballard	HD85	85	280-420	-	4	8	1130	869	506	496.9	256	0.17	0.33
Ballard	HD100	100	400-580	-	6	8	1200	869	506	527.7	285	0.19	0.35
Ballard	MD30	30	117-180	0-300	-	8	900	470	350	148.1	95	0.20	0.32
Ballard	XD200	200	412-635	223	-	-	1800	2000	500	1800.0	1000	0.11	0.20
Hydrogenics	HyPMHD30	33	60-120	0-500	-	-	668	406	255	69.2	73.5	0.48	0.45
Hydrogenics	HyPMHD90	99	180-360	0-500	-	-	1085	1582	346	593.9	360	0.17	0.28
Hydrogenics	HyPMHD180	198	180-360x2	0-500	-	-	1085	1582	690	1184.4	720	0.17	0.28
Hydrogenics	Celerity	60	300-640	0-200	-	7.5	800	375	980	294.0	275	0.20	0.22
Nuvera	Orion2	30	143	450	-	7	326	280	210	19.2	34	1.57	0.88
Powercel	S2-250C	22.5	125-250	200	-	2.5	148	480	468	33.2	34.5	0.68	0.65
Powercel	S3-335C	100	200	570	-	3	149	419	444	27.7	32.3	3.61	3.10
Proton Motor	S5	6	35-120	0-100	0.35	7	808	465	308	115.7	79	0.05	0.08
Proton Motor	S25	25	35-120	0-450	2.5	7	990	445	454	200.0	120	0.12	0.21
Nedstack	FCS 10-XXL	9.5	41-73	0-230	-	1.3	550	194	288	30.7	40	0.31	0.24
Nedstack	FCS 10-HP	10	43-73	0-230	-	1.3	550	194	288	30.7	40	0.33	0.25
											Average	0.53	0.50
											Correct average	0.24	0.29

Table 30. FC module market analysis.

Table 30 tried to consider only FC modules. A distinction between FC modules and stacks is given in chapter 2.4.3. Some producers though, define module the single stack. The absence of the module BoP systems result in lower volumes and weight and virtual higher performance. For this reason the red values have been excluded from the evaluation of the average Power Density and Specific Power.

The power range required from ships are in the order of MW, that means that to be effective fuel cell systems should have hundreds kW power ranges that can be achieved only by connecting more modules together. A well defined application for fuel cell power system on-board ship has not been defined yet and probably does not exist, for this reason FCSs will be designed case by case, highlighting the importance of fuel cell modules easy to be integrated. Indeed, the largest PEM fuel cell systems have been assembled using 10 (kW) stacks rather that modules, reaching 1 (MW) (66) and 2 (MW) (67) power. A deeper analysis of the FCSs and the choice of modules as basic components for the integration of fuel cells on-board ships is given in Chapter 2.4.2, it justify the reason of the focus that has been made on the fuel cell module state of the art assessment.

Table 30 reports the main data referred to the fuel cell modules available on the market. The analysis focused on the characteristics of volume and weights in order to evaluate the average power density. The average value has been corrected to consider only module performance, and gave as results the following power density:

0.24 kW/l and 0.29 kW/kg

These values can be used hereafter to evaluate a rough dimension of the FCS. From the assessment, other important information can be derived.

The most interesting observation concerns the ***hydrogen inlet pressure*** required by the module, that in most of the cases ranges between 7 and 8 (bara). This means that the modules are not only pressurized but use anode recirculation systems. A pressurized fuel cell works with pressures that ranges between 2 to 3 (bara) at the anode and cathode side in order to increase the fuel cell performance (68). ***The anode recirculation*** system has been introduced to increase the fuel utilization, but it proved its functionality also at easing the water removal and so providing a better water management (69). The relevant consequences at system level of a high inlet hydrogen pressure rely on the components that provide hydrogen to the FCS, the fuel storage and the fuel reformer if required. If pure hydrogen is used for example, with high pressure storages (350 or 700 bar) the limitation at 7-8 (bar) doesn’t seem to represent an important obstacle while if metal hydrides storage systems are used, high pressure release require higher working temperature and limit the usable stored hydrogen.

Other important data derived from the assessment are ***the maximum current and maximum voltage*** of the modules, of 500 (A) and 120-180 (V) respectively for the 30 (kW) range modules. These numbers are interesting for the design of higher power FCS that will consider the connection of more modules together, in order to define the current and voltage range of the system.

The data of three of the 30 (kW) range modules have been compared in order to define the electric efficiency and the general performance that could be expected from it. Due to the lack of data some values have been derived from private data and experience through backwards calculations. All the PEMFC module considered, deliver unregulated DC current.

Efficiency

The efficiency of a fuel cell could be defined as the ratio between the electrical energy produced and the Gibbs free energy of formation (70), used to define the useful energy of a system. If the irreversibility are not considered, all the energy could be converted into electrical energy and the efficiency could be said to be 100%.

$$\frac{electrical\,produced\,energy}{Gibbs\,free\,energy\,change}$$

However, it is not very useful, and is rarely done, as whatever conditions are used the efficiency limit is always 100%. While the maximum theoretical efficiency of a conventional heat/expansion engine is described by the Carnot cycle, giving the classical thermodynamics formula:

$$\eta_{Carnot} = \frac{T_H - T_C}{T_H} = 1 - \frac{T_C}{T_H}$$

For a hydrogen/oxygen reaction, no wonder that occurs in a heat engine or a fuel cell, the total input energy is equal to the energy required to produce water, said enthalpy of formation Δhf. For this reason the suitable definition of a fuel cell efficiency is the ratio between the useful energy to the total energy. However, there are two different values that can be used for Δhf. If steam is considered as reaction product, Δhf = *-243.83 (kJ/mole)*, while if liquid condensed water is considered Δhf = *=-285.84 (kJ/mole)*. The first figure is the Higher Heating Value (HHV) and the second one is the Lower Heating Value (LHV). It can be concluded that the efficiency limit (or reversible efficiency, maximum efficiency) can be written as:

$$\eta = \frac{\Delta\overline{g_f}}{\Delta\overline{h_f}} \times 100\%$$

The efficiency equation could also be expressed in voltage ratio in order to have a more convenient calculation to perform. In order to evaluate it, the theoretical maximum voltage is evaluated using HHV and LHV.

$$E_h = \frac{-\Delta\overline{h_f}}{zF} = 1.48\ V\ (HHV)$$

$$E_h = \frac{-\Delta\overline{h_f}}{zF} = 1.25\ V\ (LHV)$$

The final equation of efficiency become.

$$\eta_{HHV} = \frac{V}{1.48} \times 100\%$$

$$\eta_{LHV} = \frac{V}{1.24} \times 100\%$$

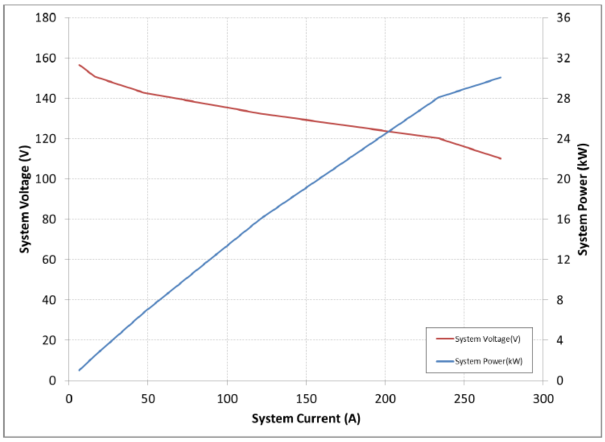
These formulas have been used to evaluate the efficiency of the fuel cell module that have been analysed in the following. Efficiency is important because is directly correlated to fuel consumption, therefore higher efficiency modules will be preferred. For the purpose of the thesis, the assessment is useful also to determine an average value of efficiency that could be used to define the general performances of a FCS, together with the previous defined number related to power density. All the considered data refer to the Beginning of Life (BoL) state, generally a stack is considered to have reached End of Life (EOL) performance once the power degrades by 20% relative to BOL power.

PEMFC comparison

Ballard MD30

Figure 34. Ballard MD30 module

For the Ballard MD30 module, a graphic with the module voltage and power curve is available. In order to define the efficiency of the system the number of cells was estimated on the base of informal information. The obtained result is in line with the performance of other Ballard modules. The MD30 is a self-humidified module able to work without a humidification unit. Moreover is characterized by the presence of graphite-based bipolar plates.



P	30	kW
Vtot	110	V
#cel	180	-
Vcel	0.611	V
ETA LHV	49%	-
ETA HHV	41%	-

Figure 35. Ballard MD30 system polarization curve and gross power

The estimated value is reported in red.

In the following the specification of anode flow, cathode flow and cooling liquid are reported. The purpose is the identification of the poison substances and of their limits.

Ballard AIR specification	
oxygen	20.90%
hydrocarbons (mole basis)	< 50 ppm
carbon monoxide (mole basis)	< 35 ppm
carbon dioxide	< 1%
ozone	< 1 ppm
sulphur compounds (mole basis)	< 0.3 ppm
hydrogen sulphide (mole basis)	< 1 ppm
liquid water @ < 5 µS/cm	< 0.5%
inorganics (including salt)	< 0.01%
particulate size	< 25 µm
NOx:	< 10 ppb
SOx:	< 1 ppb
NH_3:	< 3 ppb
VOC:	< 20 ppb
SPM:	< 20 µg/m^3
SPM:	< 5 µm diameter
Salt:	< 20 µg/m^3
Salt:	< 25 µm diameter
All Fenton's catalysts are to be avoided	

Ballard HYDROGEN specification	
H_2 quality as per SAE specification: J2719	
Exceptions to J2719:	
CO_2	< 1 ppm
CO	< 0.1 ppm
S	< 1 ppb
NH_3	< 1 ppb
Fe	<= 4 µg/h
Ni	<= 3 µg/h
Cu, Cr, Al	<= 1 µg/h

Ballard COOLING specification	
Conductivity	≤ 5µS /cm
Ethylene Glycol Concentration	≤ 50% volume
Balance DI Water Particulate Size	<100 µm
Chloride Concentration	≤0.0002%
Iron Concentration	≤0.0002%

Table 31. Ballard gas and cooling specifications

Two observations can be made: first, hydrogen specification are very tight, as already known on CO and S, but the limitation are given also for a number of other components that are never given among the specification by the hydrogen producer. Secondly, the air specification lists result to be longer than the hydrogen one, requiring high attention for the air supply from the module integrator.

Hydrogenics HyPMHD30

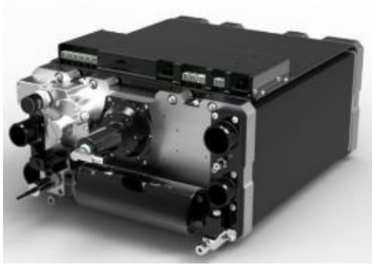
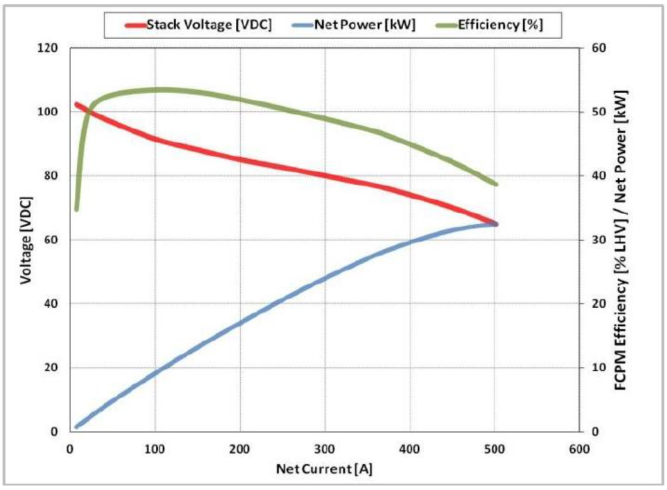


Figure 36. Hydrogenics HyMHD 30 module

For the Hydrogenics HyMHD30 module, the polarization curve and the gross power of the module is given together with a efficiency curve based on LHV of hydrogen. The former consider parasitic loads but exclude the BoP auxiliary system energy consumption as the radiator fan and the water pump.



P	30	kW
Vtot	75	V
#cel	130	-
Vcel	0.577	V
ETA LHV	46%	-
ETA HHV	39%	-

Figure 37. Hydrogenics HyPM HD30 system polarization curve and gross power

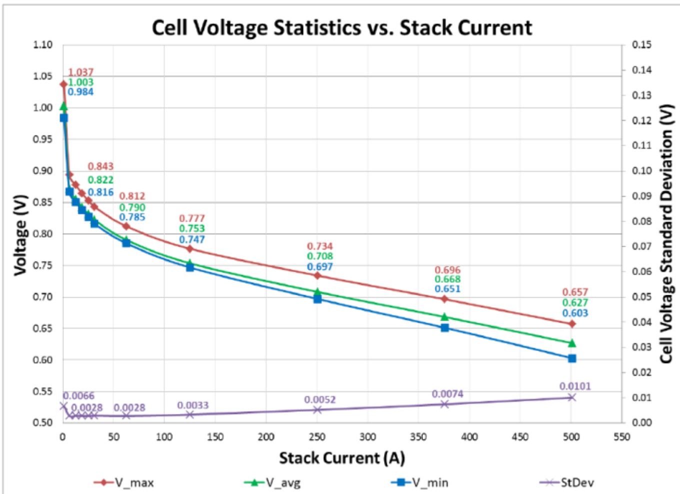
The estimated value is reported in red. In this case the number of cells have been derived from an inverse calculation of the cell tension from the efficiency curve.

No other information have been found about the Hydrogenics stacks, nonetheless, the evaluation of the performance of this module has been done because the company is able to provide interesting fuel cell racks. The former are composed by many HD30 modules, and it represent the ideal example of the modular fuel cell power system for marine application made throughout the integration of already existing automotive technology.

Nuvera Orion 30 kW

Figure 38. Nuvera Orion 30 module

The Nuvera module Orion 30 (kW), is the module that has been used during the Teseo project (71), that later has been integrated into the HI-SEA Joint Laboratory (62). Differently from the other modules, the Orion comes with basic BoP components, but it can be considered comparable to the others since like the others, the available data refer to the stack performance, considering the parasitic loads but without considering other BoP auxiliary system energy consumption. The Orion is a self-humidified module able to work without a humidification unit, characterized by the presence of metal-based bipolar plates, differently from Ballard.



P	32.6	kW
Vtot	130.3	V
#cel	184	-
Vcel	0.708	V
ETA LHV	57%	-
ETA HHV	48%	-

Figure 39. Nuvera Orion 30 system polarization curve

In the following the specification of anode flow, cathode flow and cooling liquid are reported. The purpose is the identification of the poisoning substances and of their limits.

Nuvera AIR specification	
Oxygen , dry basis	20.0 Minimum volume %
General quality[1]	Free from dust, dirt, smoke, soot, pollen, oil
Particulate Matter (PM2.5)	15 µg/m3
Particulate Matter (PM10)	5 µg/m3
Total aromatics	0.1 ppm
CO	9 ppm
CO2	500 ppm
Lead	1.5 µg/m3
Ammonia	10 ppb
Total chlorine	1 ppm
NO2 (including derivative species)	Average: 50 ppb; Peak: 150 ppb
Ozone	80 ppb
NaCl & other salt compounds	5 mg/m3
SO2 (including derivate sulfur compounds)	25 ppb
Water vapor Non-condensing	n/a

Nuvera HYDROGEN specification	
Maximum Total Gas Impurities	50 ppm
Combined N2, Ar, He, O2 and hydrocarbons	47 ppm
Total aromatics	0.1 ppm
CO	0.5 ppm
Combined CO and CO2	1 ppm
Total Chlorine	0.1 ppm
Total Sulfur	1 ppb
Ammonia	10 ppb
Mercury	1.1 µg/m3
Sodium	2 ppm

Nuvera COOLING specification	
Water Conductivity	5.0 µS/cm
SiO2	0.1 ppm
Ca + Mg	0.1 ppm
Fe	50 ppb
Al	20 ppb
Hg	50 ppb
Heavy Metals	50 ppb
Na	50 ppb
Sulfate	1 ppm
Ammonia	30 ppb
Total chlorine	0.1 ppm
TOC	1 ppm
Suspended Solids	0.5 ppm

Table 32. Nuvera gas and cooling specification

A comparison with the Ballard and the Nuvera specification shows that they are very similar. Once again, the air specification are very restrictive. As for the Ballard module, another important observation should be made on the maximum conductivity of the cooling water, < 5 µS/cm, a value that is smaller with respect to commercial demineralized water, but that is very difficult to be matched with the glycol so that there are very few product available on the market.

From the performance analysis it result that the Orion module has the highest scores. The reasons have to be searched in the working parameters. Table 33. Comparison between Ballard and Nuvera module operative data shows a comparison between some operative data. The hydrogen consumption is directly connected to the efficiency and it is a result of other parameters, the most important among which is represented by the working temperature. Temperature and pressure are the main operative parameters able to enhance the stack performance at the same stack dimensions (68). A second difference that can be noticed, is the presence of a little percentage of hydrogen in the cathode exit of the Ballard module while the Nuvera one don't have it. The reason is due to the combination of the cathode exit with the anode purge, that contain mainly nitrogen but also a small quantity of hydrogen. The Orion module have a separate channel to deal with the purge.

	Anode			Cathode			Cooling		
	close circuit			In		Out	close circuit		
	kg/h	comp	bar	kg/h	comp	comp	kg/h	comp	℃
Ballard MD30	2.3	H2	7-8	126.0	Air	Exhauts Air+H2<3%	-	Glysantin	60
Nuvera Orion 30	2.2	H2	8-10	123.8	Air	Air	2.7	Glysantin	85

Table 33. Comparison between Ballard and Nuvera module operative data

Finally, a comparison between the hydrogen consumption, air consumption and water production have been made, considering factory data and stoichiometric values evaluated with the following formula (70):

$$Hydrogen\text{:}\ \ Q\ [kg/h] = \ 0.037 * I[A] * cell\ number * 10^{-3}$$

$$Oxigen\text{:}\ \ Q\ [kg/h] = \ 0.29 * I[A] * cell\ number * 10^{-3}$$

$$Water\text{:}\ \ Q\ [kg/h] = \ 0.33 * I[A] * cell\ number * 10^{-3}$$

Table 34 shows the obtained results. An average of 28% and 107% increased flow of hydrogen and air respectively is required by the modules. No data are available about the water production, so the stoichiometric production will be considered. The modules uses anode recirculation system, therefore there is no anode outlet. The hydrogen surplus flow is required to cover crossover and losses during purges. The cathode side on the contrary is an open circuit, generally, in order to increase the performance a higher air flow is given to the cells of about two times the stoichiometric request, it is indicated as $\lambda=2$.

Ballard MD30										
I [A]	273		Stechiometric cons.		30.0	kW	Factory data		30.0	kW
# cell	180	H2	1.818	kg/h	0.061	kg/kWh	2.3	kg/h	0.078	kg/kWh
V [V]cell	0.611	AIR	61.959	kg/h	2.063	kg/kWh	126.0	kg/h	4.196	kg/kWh
V [V]tot	110	H2O	16.216	kg/h	0.540	kg/kWh	-	kg/h	-	kg/kWh
Hydrogenics HyPMHD30										
I [A]	400		Stechiometric cons.		30.0	kW	Factory data		30.0	kW
# cell	130	H2	1.924	kg/h	0.064	kg/kWh	-	kg/h	-	kg/kWh
V [V]cell	0.577	AIR	65.565	kg/h	2.186	kg/kWh	-	kg/h	-	kg/kWh
V [V]tot	75	H2O	17.160	kg/h	0.572	kg/kWh	-	kg/h	-	kg/kWh
Nuvera Orion 30										
I [A]	250		Stechiometric cons.		32.6	kW	Factory data		32.6	kW
# cell	184	H2	1.702	kg/h	0.052	kg/kWh	2.2	kg/h	0.072	kg/kWh
V [V]cell	0.708	AIR	58.000	kg/h	1.781	kg/kWh	122.5	kg/h	4.079	kg/kWh
V [V]tot	130	H2O	15.180	kg/h	0.466	kg/kWh	-	kg/h	-	kg/kWh

Table 34. Modules data consumptions

PEMFC Conclusions

Some final remarks are given on the assessment of the commercial fuel cell modules:

- Different power sizes are available, even if a standard is not present, it is possible to identify the *30 (kW) as a power size* supplied by many OEMs producers.
- The supply level of the modules in terms of completeness of auxiliary systems, enclosure and connection is very different from the OEMs.
- The average values indicating the performances of a commercial 30 (kW) module have been found, reported in Table 35.

Average values		
H2	0.07	kg/kWh
AIR	4.14	kg/kWh
H2O	0.53	kg/kWh
ETA LHV	51%	-
ETA HHV	43%	-
Power Density	0.24	kW/l
Specific Power	0.29	kW/kg

Table 35. PEMFC average performance data

HTPEMFC

High temperature PEMFCs are relatively new products and for this reason, there are few OEMs who are able to provide it on the market. Indeed only one product has been found available on the market, the Serenergy Serenus fuel cell module, available with 1, 2.7 and 5 (kWe) output power. HTPEMFC present lower performances with respect to the low temperature PEMFC, due to the great difficulties in the management of humidity and temperature control. Moreover, this technology is less developed than the low temperature fuel cells technology, for this reason it cannot count on the same reliability. However, HTPEMFC have an important advantage against PEFC, the pollutants tolerance. Since the majority of hydrogen fuel is produced by fossil fuel, the tolerance of higher amount of CO highly reduce the required purification. Figure 40 shows a scheme with the fuel processing reaction and the related fuel cell technologies able to accept the reformed fuel with an increased level of purification (72). Higher level of purification require higher amount of energy and costs.

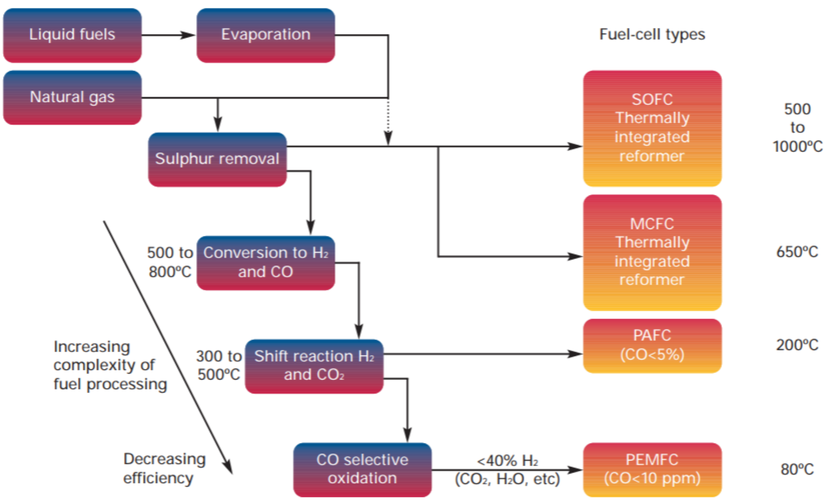


Figure 40. Fuel processing reaction

Moreover, the possibility of using hydrogen fuel with higher percentage of CO permit the use of portable reformer, in this way other primary fuel could be used instead of pure hydrogen, like LNG, LPG, Methanol or others, to produce hydrogen on-board. Since hydrogen storage systems performances are very poor, the use of hydrogen rich alternative fuel to be reformed on-board could enhance the system energy density. Indeed, that is what Serenergy is pursuing with its H3 Reformed Methanol fuel cell module, composed by a HTPEMFC with an integrated reformer. Both the modules have been analysed in the following.

Serenergy Serenus

Figure 41. Serenergy Serenus S120 stack

The Serenus stack is a self humidified HTPEMFC module ready to be integrated. The module is available with 1, 2.7 and 5 (kWe) of maximum power and could be fed with hydrogen rich syngas, with high tolerance of CO, up to 5%. The CO tolerance of low temperature PEMFC range between 0.1 (ppm) to 50 (ppm) (0.00001% to 0.005%).

Few data of the Serenus module have been found. An estimation of the efficiency have been found starting from the stack polarization curve published in the technical sheet. An interesting observation could be done on the current density at which the stack is operated. Since the *active area* value was not available, assumptions have been made on the bases of the performance and data of the H3 stacks. It is possible to state with enough confidence that the *current density* of the operative stack is below 0.3 (A/cm^2). A low current density involve a poor power density in terms of weight and volume. Table 36 reports the collected data, that confirm the poor value of power density and specific energy of the stack, confirming the aforementioned analysis.

Serenergy HTPEM						
Model	Type	Power	Tension	Current	Consumption	ETA el
		kW	V	A	l/kWh	%
Serenus	S120	5	60-85	130	-	~40%
L	W	H	Volume	Weight	Power Density	Specific Power
mm	mm	mm	l	kg	kW/l	kW/kg
729	444	483	156.3355	68	0.03	0.07

Table 36. Serenergy Serenus performance analysis

Serenergy H3 S120

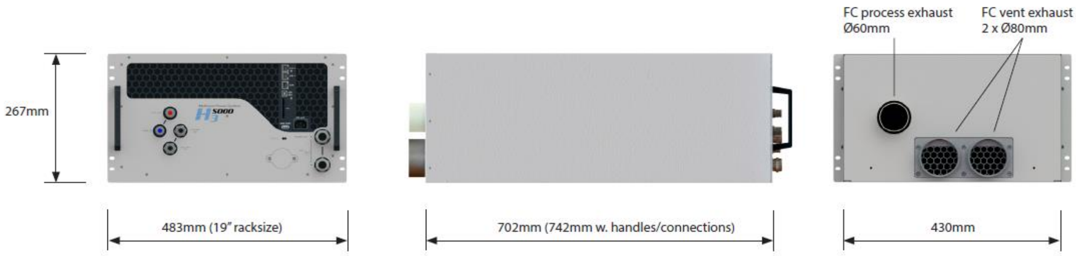


Figure 42. Serenergy H3 S120 module

The most promising fuel cell module for marine application for the short term application is the Serenergy H3 S120. It is composed by an internal reformer coupled with a self-humidified 5 (kWel) high temperature PEMFC. The module has been designed to be directly feed with a Methanol base mix (60% CH3OH), without the necessity of intermediate reformer or humidification. The technical datasheet, reported in Table 37, is sufficient to evaluate the module power density and rough performance but don't give the possibility to distinguish the performance of the reformer from the ones of the stack. What could be noticed, is that the power density and the specific energy of the HTPEMFC seems to been increased since the H3 module presents similar performance in comparison with the Serenus module even if a reformer is present.

Serenergy HTPEM+Reformer						
Model	Type	Power	Tension	Current	Consumption	ETA el
		kW	V	A	l/kWh	%
H3	5000	5	42-58	-	0.8	45%
L	W	H	Volume	Weight	Power Density	Specific Power
mm	mm	mm	l	kg	kW/l	kW/kg
702	483	267	90.53062	65	0.06	0.08

Table 37. Serenergy H3 S120 module performance analysis

The module is provided with all the connections and casing so that it is ready to be installed. Recently it has been the subject of a dedicated work package of the JOULES project (73), a detailed report of its performance is available (74). The module is composed by two principal components, the HTPEMFC stack and the Methanol Reformer, Figure 43. Internal view of the H3 S120 module. The output DC current is regulated, thanks to the presence of an internal DC/DC converter that is also used to control the module. The module is liquid cooled and requires a high air flow, three times higher than a PEMFC module.

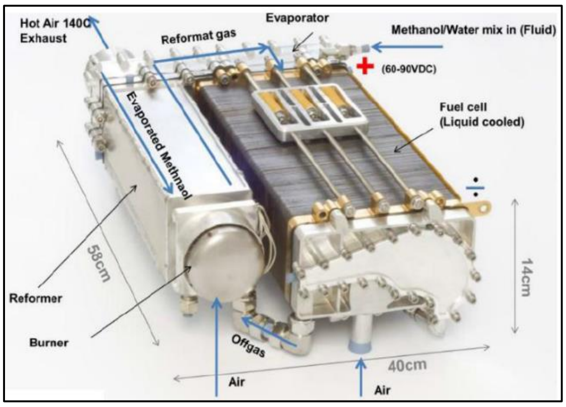


Figure 43. Internal view of the H3 S120 module

From the polarization curves in Figure 44, it is possible to derive the influence of temperature in the stack capability of CO tolerance. A second information that could be derived from the I-V curves is the low current density at which the cells are operated. From (74) it has been possible to derive the required data to evaluate the stack efficiency and the module efficiency. Table 38 resume the information. The bold numbers are the ones taken from (74), the estimated value required to link the polarization curve to the other data is the active area (orange). Current density was derived from the polarization curve to find the cell voltage. A cross check with the available data confirmed the supposed stack cell number (120). In order to evaluate the performance of the module near the maximum power an extrapolation of data was made (grey column). Finally, an estimation of the global module efficiency has been calculated, showing a value of about 22%.

Load %	**75%**	**85%**	95%	load
P	**3750**	**4250.0**	4750	kW
J	0.20	0.24	0.275	A/cm2
Vcel	0.64	0.62	0.6	V
Vtot	**76.5**	**74.3**	72	V
I	**49**	**57.2**	66	A
Area	240.0	240.0	240.0	cm2
ETA LHV stack	0.51	0.50	0.48	-
ETA HHV stack	0.43	0.42	0.41	-
ETA el	0.46	0.46	0.46	-
Fuel CH3OH	0.83	0.97		g/s
	1.01	1.04		l/kWh
	2.99	3.49		kg/h
	16.54	19.33		kW
ETA LHV module	23%	22%		ETA
Air Flow	11.90	13.88		g/s
	42.84	49.97		kg/h
	11.42	11.76		kg/kWh

Table 38. H3 S120 performance analysis

HTPEMFC Conclusions

The HTPEMFC represent the efforts to use reformate hydrogen inside PEM fuel cell without the necessity to have a high and complex purification system between the reformer and the stack. The reason why it is considered of high interest, especially for mobile applications but not only, as Japan experience demonstrate, is given by the possibility to use primary fuels different from pure hydrogen. Figure 44 shows the polarization curve of the Serenergy HTPEM with different percentage of CO and its relation with temperature. It is possible to observe the capacity to tolerate large quantities of CO, up to 50000 (ppm). By contrast low temperature PEMFC are able to withstand only 0.1/0.5 (ppm). This fact entail important consequences in the energy storage performance, fuel distribution and infrastructure. For this reason it is considered the most promising solution to be implemented on board ships. However, the performances in terms of power density and specific power of the HTPEMFC result to be much lower with respect to the PEMFC, while the energy density and specific energy of the storage system is affected by the required presence of a reformer on board the vehicle. Finally, the use of primary fuels derived from fuel oil, doesn't reduce the amount of produced GHGs but it increased it instead with respect of ICES fuelled by fuel oil.

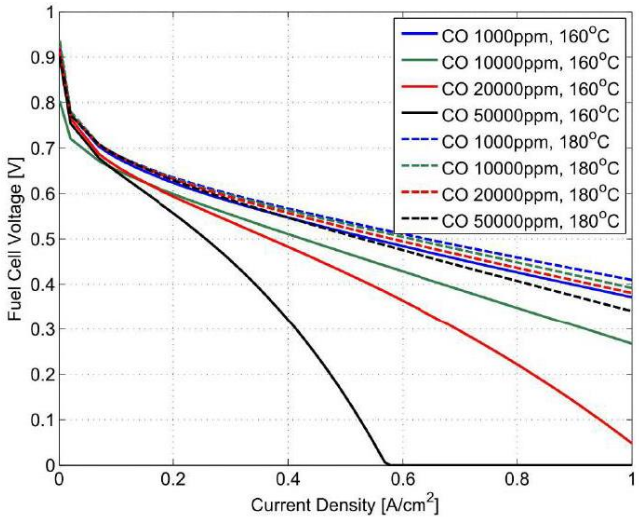


Figure 44. Polarization curve of H3 S120 stack

2.4 Fuel Cell System (FCS) design

In order to consider the installation of new power generators on board a ship, an analysis of the system design is required. Generally, the energy system is broken down into two main parts: The Power Generator System and the Storage System, typically represented by the ICE System and the Fuel Oil storage respectively. Between them, fuel treatment systems are usually required, as showed in (Chapter 2.1), they can require complex energy consumer machines. In order to optimize the available space, to reduce the connected risk of fire and incidents, to confine in a single space all the "problems" related to the energy production, historically the power generators together with the auxiliary systems and the fuel treatment systems are installed in a single space called Machinery Room. International conventions (IMO), countries administrations and classification societies rule the design of the machinery room for safety purpose. Due to the characteristic of fuel cell systems, the FCS has been considered separately from the fuel processing system, because some configurations don't require their thermal coupling and other don't require the fuel treatment system at all, like the case of the use of pure hydrogen.

In the following a general design of a PEM Fuel Cell System is presented, such that would able to comply against the IMO rules still under construction and the technical characteristics of the fuel cell technology it's made of. Two important aspects related to both these aspects are introduced.

IMO scheme

Presently, Part E of the IGF code (75), dedicated to the use of fuel cell systems, is under construction by the IMO Maritime Safety Committee (MSC) and will be probably released as a draft during 2021/2022. The code will provide among all two important things: Terminology and FCS power installation scheme. The former is strictly related to the terminology, it defines the boundaries of the "Fuel Cell Space", the equivalent of the Machinery Room. Its definition is fundamental since the presence or absence of determined FCS components and the relations between them will strongly influence the design of the FCS. Figure 45 shows the FCS diagram produced by the IMO Sub-Committee on Carriage Of Cargoes And Containers mentioned on CCC4/WP.3 Annex 2 and considered in the IGF draft too. The scheme shows the components of a general fuel cell power installation supposing to consider any kind of fuel cell technologies.

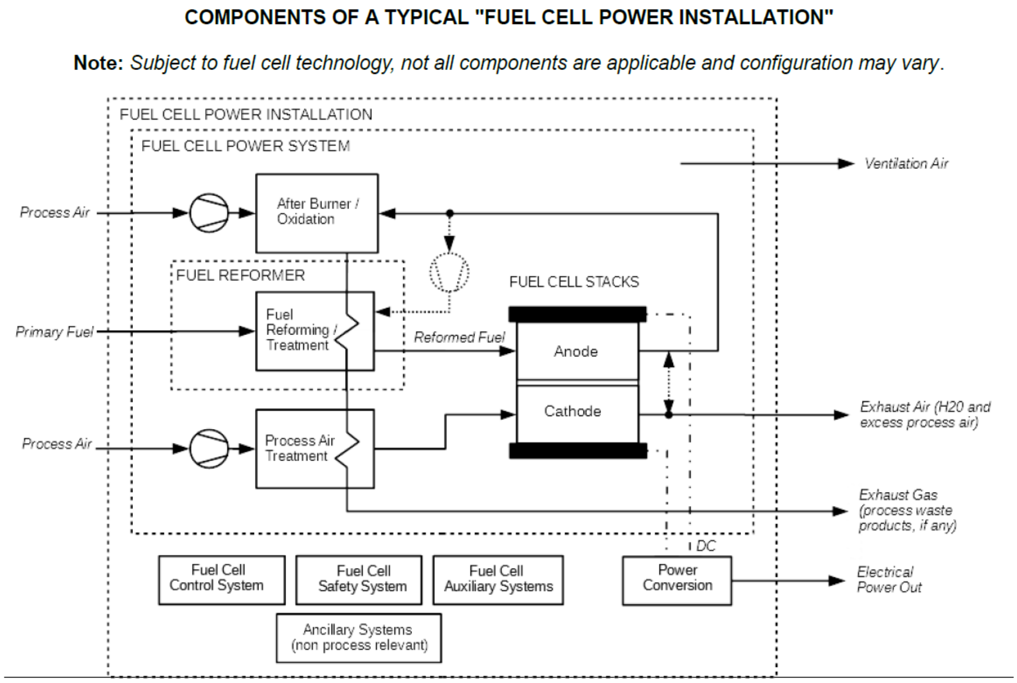


Figure 45. CCC4/WP.3 fuel cell system diagram

The present IMO FCS configuration don't consider the possibility to have a reformer unit outside the "fuel cell space", because the reformer is considered only as a coupled system fitted on the fuel cell section. But there are many different FCS configurations that don't permit the coupling of the fuel cell with the reformer so that the former could be considered as a separate unit, not necessarily to be installed inside the "fuel cell space".

Modularity

Many characteristics define the peculiarity of fuel cells and fuel cell systems. Among all, modularity is thought to be the most important. Fuel cell systems are often considered in comparison with ICEs, as possible substitute for a future low emission ships. For this reason a misleading image of the FCS as a defined power generator took shape and it often distract the ship designer from the important characteristic, modularity. Indeed, fuel cells are like batteries, composed by elements, stacks, modules, easy to integrate to design power systems with different tension, current and power size. This aspect should be considered not only by the ship designer but also by the rule maker, in order to enhance fuel cell systems performance, safety and reliability. Due to this important characteristic, the challenge that have to be faced is represented by the definition of the basic module, the minimum power unit to be considered for the integration on-board a ship, together with the system component hierarchy that follow.

In the following, an analysis of different FCS, considering different primary fuels and fuel cell technology is presented. The final goal is the definition of a PEM FCS components lists together with a tentative definition of the FCS terminology and a FCS design able to comply with the rules and to enhance the fuel cells characteristics.

2.4.1 FCS types

A fuel cell system is generally composed by three main parts: the fuel processor, the fuel cell power section, the power conditioner. Figure 46 (70) shows a scheme with the fuel its energy flows. Not all the system require the fuel cell processor nor the fuel processor unit is equal for any kind of fuel cells, it depends on the primary fuel and the fuel cell electrolyte. Therefore, two configuration can be derived, the first considers the use of a primary fuel that requires a fuel processor, the second consider the direct use of the fuel inside the fuel cell power section. In the following a description of the FCS types is given considering the three fuel cell types that have been previously found suitable for marine application, PEM, HTPEM and SOFC.

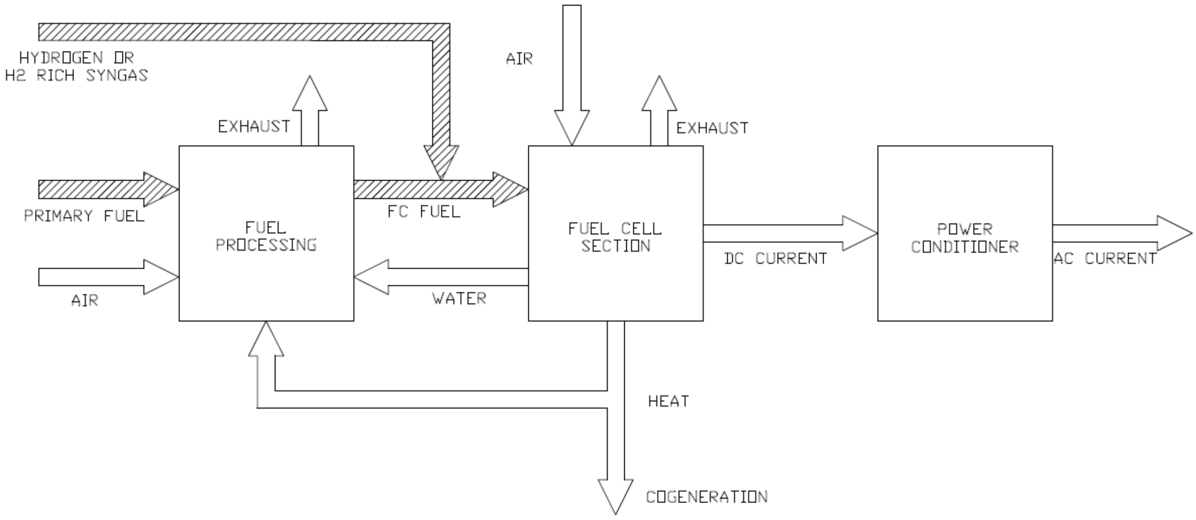


Figure 46. General scheme of FCS

Starting from the general scheme of Figure 46, an analysis of the possible FCS configuration is presented taking into account the possibility to feed the FCS with the fuels that have been found suitable for this application during the comparative study of alternative fuels (Chapter 2.2), namely Hydrogen, Natural Gas, Petroleum Gas, Methanol. Also fuel oil (diesel) will be considered as primary fuel for a reformer processor unit. The analysis will consider the system configuration taking into account the possibility to thermally couple the fuel cell and the steam reformer. The former is the reformer technic with the higher yield, but since it is a endothermic reaction it require heat from an external source. The thermal coupling could enhance the global system efficiency, it permits the use of the anode exit flow inside the reformer unit, more important, it requires the installation of the reformer unit near the fuel cell unit. The last fact has important implication in the definition of the “fuel cell space” as will be showed in the following. In order to define the possibility to thermally couple the fuel cell and the reformer, a useful diagram is available in Figure 47 (76).

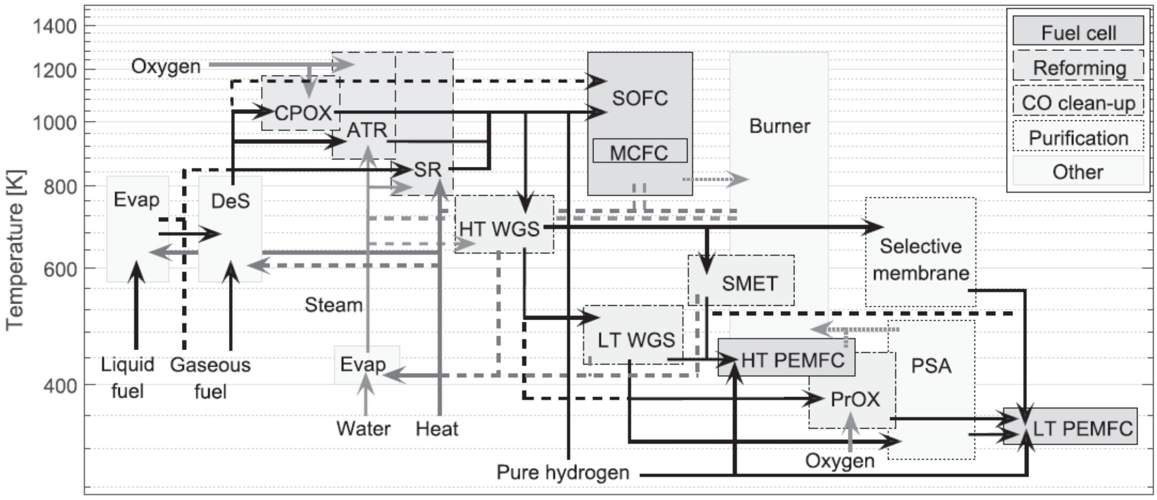


Figure 47. Overview of on-board fuel processing steps in fuel cell systems, with indication of their operational temperature. The solid black lines indicate the common process flow

Using literature data and the information derived from the diagram in Figure 47, an assessment of the FCS architecture has been done distinguishing for each fuel cell type, and different fuels among the one considered from the alternative fuel assessment. In order to complete the thermal ranges of reformer and fuel cells, Table 39 has been constructed (77) (78) (79).

		Diesel	**Methanol**	**NG**	**PG**
Reformer Unit	**Reaction**	**°C**	**°C**	**°C**	**°C**
Steam Reformer	Endothermic	700-900	300-400	700-900	700-900
Partial Oxidation	Exothermic	800-1000	700-800	800-1000	800-1000
Autotherma Reformer	Neutral	700-900	500-600	700-900	700-900

°C	**Fuel Cell Stack**
70-90	**PEMFC**
180-200	**HTPEMFC**
800-1000	**SOFC**

Table 39. Temperature comparison between reformer unit and fuel cell stacks

The thermal coupling of fuel cell and reformer is significant in the case of steam reformer, since require heat form external sources. Steam reformer is often considered as first choice since has a higher yield, but for reaction speed also ATR is considered convenient. ATR and Partial Oxidation reformer units don't require heat from external sources, for this reason the benefit for an integration is reduced or excluded.

PEMFC

Fuel	**Evaporator**	**Reformer**	**Termal coupling**	**Fuel Cell Type**
Hydrogen	no	no	no	PEM
NG	no	yes	no	
LPG	no	yes	no	
Methanol	yes	yes	no	
Diesel	yes	yes	no	

Table 40. PEMFC-Reformer unit compatibility

Hydrogen. The Low Temperature fuel cell is able to be directly fed with hydrogen or hydrogen rich syngas with very strict requirements in terms of impurities. Due to the low temperature (~80 °C) the produced heat is not compatible with any type of primary fuel reformer needs. Figure 48 shows a typical system configuration. The modern fuel cell modules, as the one analysed in (Chapter 2.4) are self-humidified, therefore they don't require the presence of humidifier at the entrance flows.

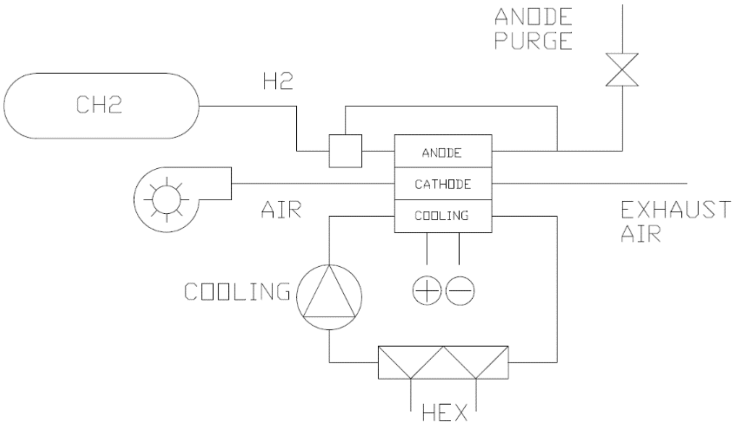


Figure 48. PEMFC scheme

Other Primary fuels. The low temperature don't permit the coupling with any kinds of reformer. For this reason the fuel cell section and the fuel reformer unit are always considered as separated unit. Figure 49 shows a general scheme of a FCS with a reformer unit. Either kind of primary fuel considered require high level of purification that make this configurations costly in terms of energy and performance.

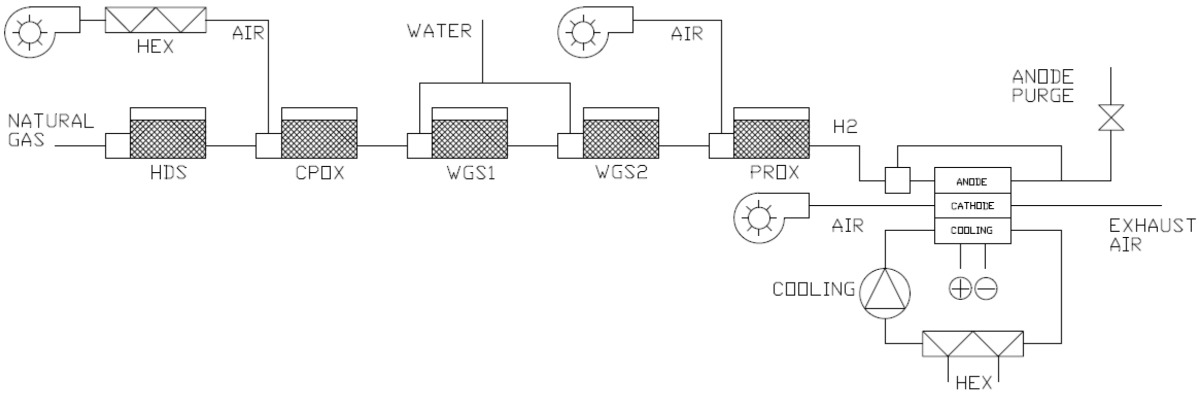


Figure 49. PEMFC scheme equipped with Methane steam reformer and purification unit

HTPEMFC

Fuel	Evaporator	Reformer	Termal coupling	Fuel Cell Type
Hydrogen	no	no	no	HTPEM
NG	no	yes	no	
LPG	no	yes	no	
Methanol	yes	yes	yes	
Diesel	yes	yes	no	

Table 41.HTPEMFC-Reformer unit compatibility

Hydrogen. Like the low temperature PEM, HTPEMFC are able to be fed directly with hydrogen, with the advantage to tolerate higher level of impurities (CO), permitting the use of less purified, therefore less expensive hydrogen fuel. No reformer is required in this case and the FCS scheme is the same presented in Figure 48. The Serenergy Serenus stack previously analysed, present a open flow configuration that differ from the other low temperature PEMFC module evaluated in (Chapter 2.4). For this reason the configuration could be different (Figure 50). But there's no reason to implement an anodic recirculation system to HTPEMFC too.

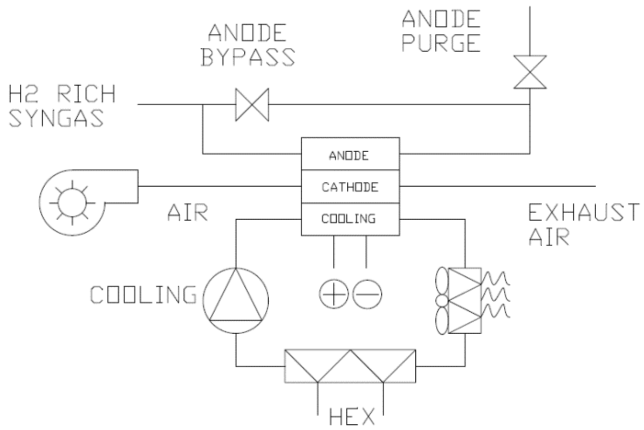


Figure 50. HTPEMFC scheme without anode recirculation

Methanol. As demonstrated by Serenergy with the H3 S120 module, the HTPEMFC favour the use of methanol as primary fuel thanks to the temperature compatibility between the fuel cell stack and the reformer unit. This kind of fuel cell require 160-180℃ or more to operate, while the steam reformer unit works at about 300℃. For this reason the methanol reformer unit is likely to be integrated within the fuel cell section or fitted to it. In the case of the H3 S120 module, as showed by Figure 51. Serenergy H3 S120 FCS scheme the anode exit flow is used inside the reformer while the heat extracted by the module liquid cooling system is used inside the methanol evaporator first and the reformer later.

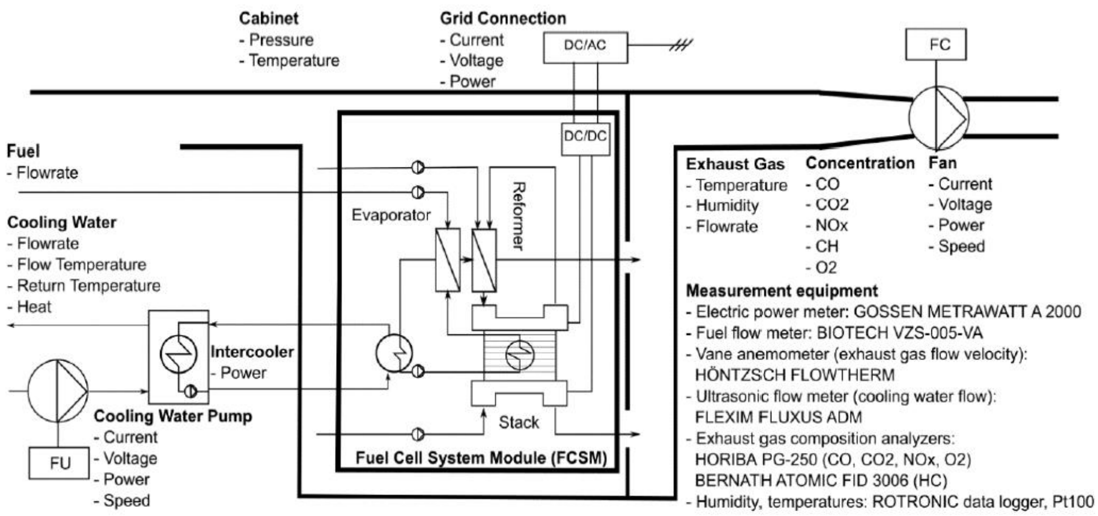


Figure 51. Serenergy H3 S120 FCS scheme

Other primary fuels. In the case of other primary fuels, Natural Gas, Petroleum Gas or diesel (fuel oil), the HTPEMFC could be considered as the low temperature PEMFC, since the high working temperature of steam reformer make difficult or useless the coupling of these systems. In the case of a open flow anodic configuration, the anode exit flow could be burned inside the reformer to enhance the efficiency, but it would be preferable to install an anodic recirculation system on the fuel cell stack.

SOFC

Fuel	Evaporator	Reformer	Termal coupling	Fuel Cell Type
Hydrogen	no	no	no	SOFC
NG	no	no	yes	
LPG	no	yes	yes	
Methanol	yes	yes	yes	
Diesel	yes	yes	yes	

Table 42.SOFCC-Reformer unit compatibility

Hydrogen. The SOFC could be fed with hydrogen rich flow. Moreover, with dead-end configurations or anode recirculation system, a SOFC directly fed with hydrogen could reach high efficiency, of the order of 60% (80), thanks to higher working temperature.

Natural Gas. NG is the ideal fuel for a SOFC FCS. The fuel cell is able to operate with a direct flow of methane or natural gas. Indeed, to speed-up the reactions SOFC are usually provided with a pre-reformer unit fitted within the stack. Figure 52 shows a general scheme of a FCS for a natural gas fed SOFC.

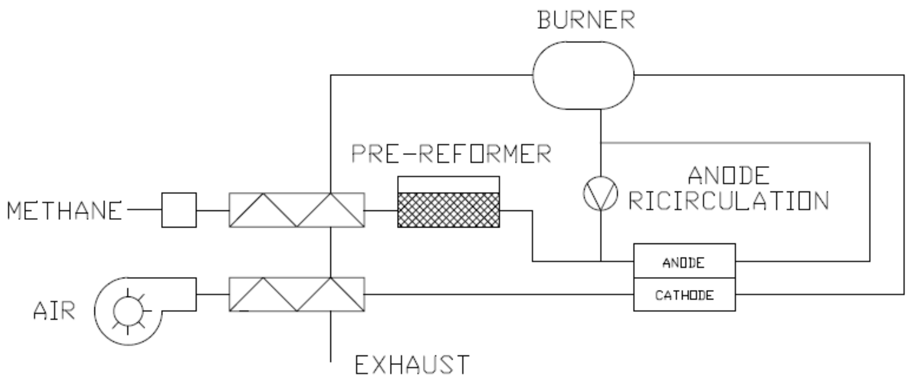


Figure 52. Basic SOFC scheme

Other primary fuels. Due to the high working temperature, the SOFC could be thermally coupled with any primary fuel steam reformer unit. For this reason, even if the reformer could be considered a separate unit from the fuel cell, it is favourable the installation inside the same space.

Hybrid system with batteries

An important aspect of fuel cell systems is the dynamic performance. Indeed it has been demonstrated (81) (61) that the dynamic performance of the system depends on the air blower/compressor performance. Large FCS for ship application though, don't have to comply with high dynamic load in principle, but a deeper analysis is required. The FCS is able to work without batteries but the experience showed the convenience to the presence of a battery pack able to ease the FCS load profile in critic situation, to support the start-up procedures and power pick cover.

The ferry AMPERA, Figure 53, represent the first ship totally propelled by Lithium-ion batteries. The project demonstrated the feasibility of an ALS, but it rise the fundamental problem of the limited energy storage, that limit the ship range. Moreover batteries suffer of long recharging time. Batteries are able to supply large currents instantly while suffer the energy capacity, for this reason battery&fuel cell hybrid system are developed and used in every mobile application. The hybrid system permit to exploit both the technologies.

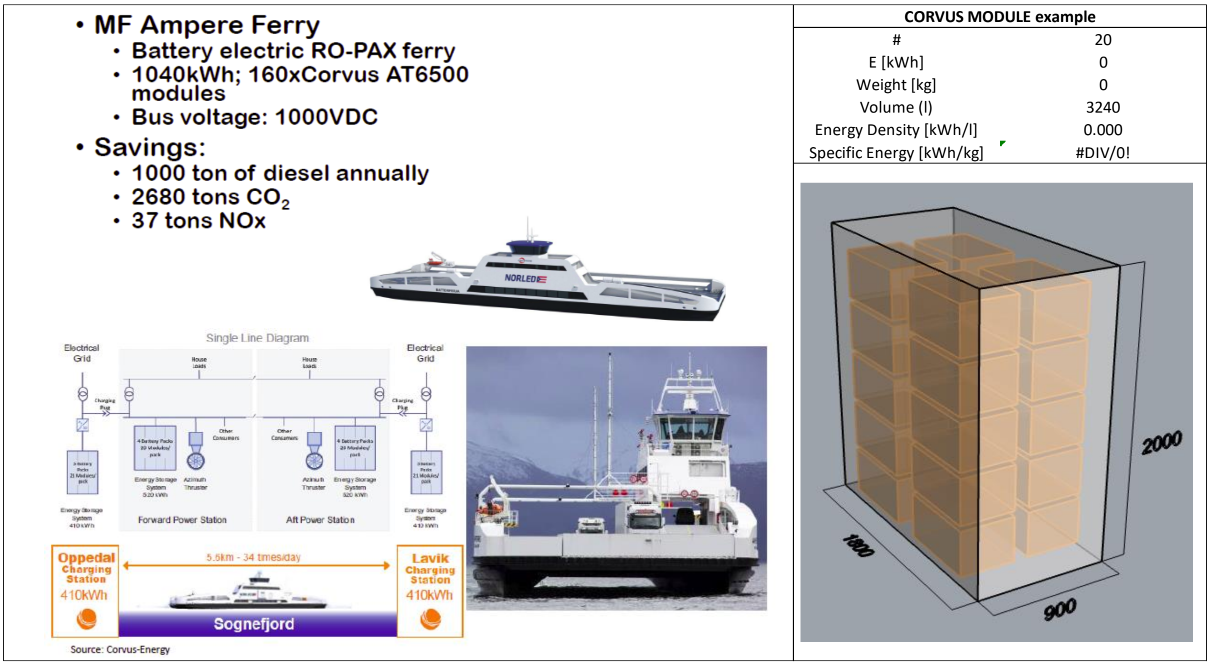


Figure 53. Ampere electric-powered ferry

Table 43 report a market Lithium-ion battery stack survey that has been conducted for the preliminary study of a fuel cell based research vessel (box at the end of the paragraph). The table shows the energy performance of different stacks. It has been used to compare the available products before the engineering of a battery module for the FCS, Figure 53.

	MASTERVOLT MLI12/320	RELION 12/300	CORVUS AT6500-250-48	EST50-525
Type	LiFePO4	LiFePO4	Lithium NMC	LiFePO4
Price [€]	3300	3250	8600	
Certified	? no	? no	DNV-ABS-LR	LR
kW price [€]	1383.6	846.4	**1291.3**	
Capacity [Ah]	180	300	150	100
Tension [V]	13.25	12.8	44.4	52
Energy [kWh]	2.4	3.8	6.7	5.2
Cycles	2000 (80%DOD)	2000 (80%DOD)	>2000?	5000 (80%DOD)
L [mm]	341	491	590	540
H [mm]	197	227	330	505
W [mm]	355	267	380	240
Volume [l]	23.8	29.8	74.0	65.4
Weight [kg]	31	43	70	47.5
BMS	yes	? no	yes	yes
Energy Density [kWh/l]	0.10	0.13	0.09	0.08
Specific Energy [kWh/kg]	0.08	0.09	0.10	0.11

Table 43. Li-Ion stack market assessment

Inside the HI-SEA Laboratory a AC/DC converter will be used to simulate the presence of a battery pack in order to define the best control strategy and sizing. Preliminary test data have been analysed and used to define the schematic P&ID of the above mentioned fuel cell research vessel, Figure 55. Following the FCS architecture explained in the following, a hybrid system has been designed, Figure 54.

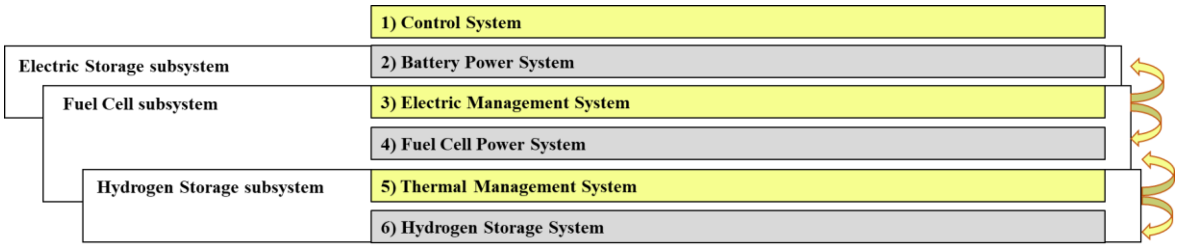


Figure 54. Example of the sub-system integration based on the developed FCS architecture

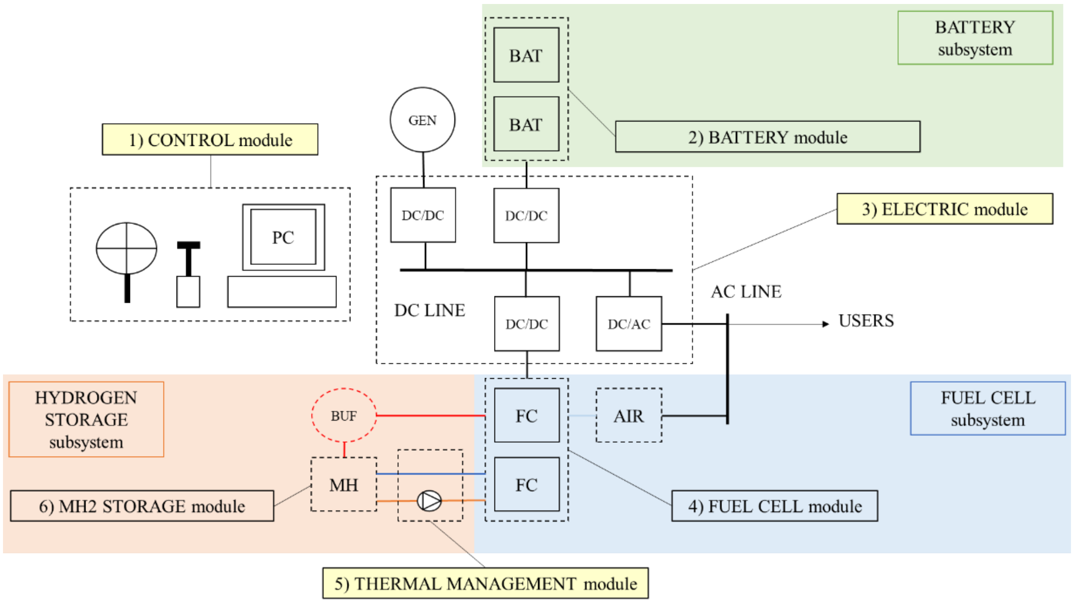


Figure 55. Example of P&ID of fuel cell Hybrid system with Batteries and MH2

It is acknowledged that the analysis of hybrid system represents an important aspect of the FCS. The theme has been presented but not developed during the thesis because it is not the goal of the study and moreover it represents the subject of another research project that is under development inside the HI-SEA Joint Laboratory in collaboration with Fincantieri.

2.4.2 FCS architecture

The previous analysis demonstrated that there is not a single FCS design, that it depends from the primary fuel that is used and the fuel cell kind. The most general scheme that could be considered for a FCS is the one in Figure 51, but it result insufficient to the purpose of ship integration. As result from the context analysis, it has been chosen to develop the study of a FCS made by low temperature PEMFC fuelled by hydrogen. In the following a tentative architecture of the system is proposed, with the goal to outline a configuration able to ease the on-board integration and to help the definition of terminology and rules.

BoP components

In order to proceed with the identification of a FCS configuration able to be reproduced with any kind of PEMFC fuelled by hydrogen while complying with the present and future rules, a list of the system component should be analysed. A distinction is made in order to equalize any kind of fuel cell system OEM’s supply. From the market review, the components of Table 44 have been found to be the basic supply. OEMs are able to supply also fuel cell stacks without any auxiliary system, but the majority of OEMs tend to have a more complete product to guarantee high level of integrations and the good operation of the stack.

L1	Stack with # cells (**L0**)
	End plate
	Front plate with manifolds
	H2 Ejector & Recirculation system
	Cooling Regulator
	CVM

Table 44. List of Level 1 components supplied by OEMs

The fuel cell supply has been identified as Level 1 (L1), as better explained later on. In order to complete a fuel cell system, other components are required. Table 45 reports a tentative list of the main components of a PEMFC FCS. The list is divided into process lines, in particular the following lines have been considered: Anodic line (Hydrogen), Cathodic line (Air), Cooling line, Electric line, Control. For each line, a distinction among the components installed at the inlet and at the outlet of the fuel cell stack (L1) is made. The components on the list represent the auxiliary systems of the FCS and are generally called as Balance of Plant (BoP).

IN	OUT	Other
Anode Line		
Anode Main valve	Anode Water separator	Anode Purge line
Anode Humidifier		
Anode pressure regulator		
Cathode Line		
Air Blower	Cathode Water separator	
Air Filters		
Cathode Humidifier		
Cooling Line		
Cooling Pump	Cooling Heat Exchanger	Bypass
Deionizing filters		
Electric Line		
24V aux	DC distribution board	Protections
	DC/DC Converter	Diodes and switches
	DC/AC Converter	Batteries
Control		
Sensors	Sensors	PLC
Valves	Valves	
	Switches	

Table 45. PEMFC FCS BoP main component list

Level of integrations

Once the BoP is defined, the main goal of the FCS architecture design is to define a configuration scheme through which integrate the FCS on-board the ship. In order to fulfil the goal, the BoP components and related connections (pipes, wire, boxes, sensors, protection an others), have been divided into four levels of integration.

- ***Level 0 (L0)***, has been identified in the fuel cell or rather the fuel cell stack (as defined by IEC 62282 standard). L0 is the component that is engineered and integrated by the OESs producer in their products.
- ***Level 1 (L1)***, has been defined as the fuel cell stack integrated with the gas manifolds, the

Control Voltage Monitor (CVM) and all the BoP components required to control the stack. Table 44 give a list of the BoP components considered in L1, that correspond with the basic supply of a fuel cell OEMs. Indeed, L1 components are not sufficient to control the stacks, but are considered strongly related with the stack dimension and characteristic so that are designed and produced together with it. This supply is often referred as "stack", even if result in contrast with the IEC definition, hereafter L1 will be also indicated as stack or stack system.

From the experience maturated during the development of the research projects conducted with Fincantieri, it has been found that L1 could not be considered as a standard basic system able to be integrated on-board the ship. The reason relay mainly on the absence of a supply homogeneity among the fuel cell OEMs products available on the market. At the present, there are not product specifically designed for marine applications (excluding small DMFC – Efoy (82)). Depending on the supplier, some automotive and land/based products results to be too bare or too specific. Some shipbuilder will try to develop their own technology and probably the first fuel cell marine applications will make use of highly customized systems. But for future large applications of fuel cells a fixed level of integration have to be established. The proposed configuration take into account the last draft of Part E of the IGF code (actually under development) together with the IEC standards dedicated to fuel cells systems and ships electrical installations.

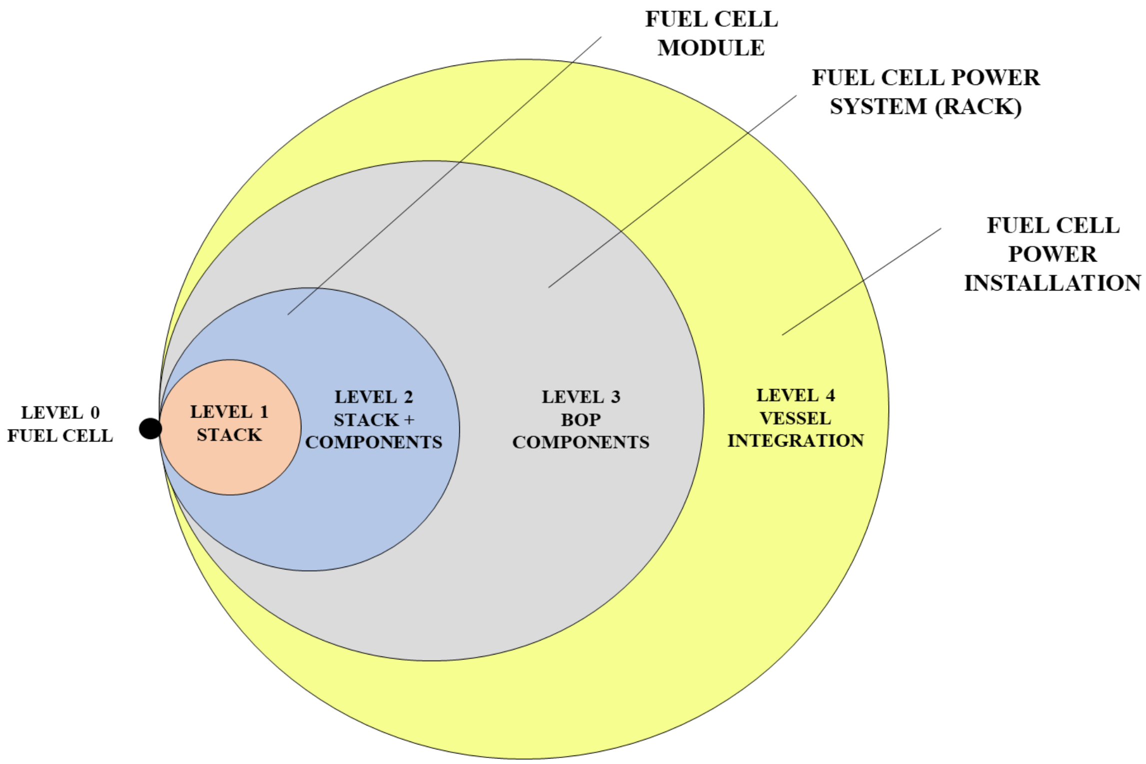


Figure 56. FCS level hierarchy

Figure 56 resume the hierarchy of the integration levels that have been designed. The core level of FCS integration has been defined as the "Fuel Cell Module". Due to the characteristic of modularity, the higher level consider the integration of more modules has been called "Fuel Cell Power System" or "Fuel Cell Rack", while the last level of integration has been called "Fuel Cell Power Installation". In the following a detailed explanations of these levels is reported.

- ***Level 2 (L2).*** After the definition of L1 and the decision to not consider it as the basic element of the FCS, the ***"Fuel Cell Module"*** was defined as L2. The most peculiar characteristic of L2 is the integration of L1 and all the BoP required to control the fuel cell stack inside a closed box provided with the fluid and electric connection. Figure 57 shows a scheme of the fuel cell module with a brief list of BoP components integrated inside, the inlet and outlet connections. The module should be considered as a black box from the ship builders, it means that the anode recirculation system, the fuel cell humidification, the voltage cell monitoring and alarms, the basic stack control more in general, should not be of the ship builder concern. Moreover, from the rule maker point of view, L2 represent a standard power generator module just like ICEs or Batteries, indeed modular like batteries but provided with fuel and air like internal combustion engines. As showed in Chapter 2.4.1 fuel cell modules are available with one or more stacks integrated inside, for this reason it has been left the possibility to have more stacks inside the modules (like having more cylinders in a ICE). The module should be designed to fulfil marine requirements like high level of inclinations, vibrations, and shock from an environmental point of view. Dimensions, weight, form and connection should be as such to permit the installation inside the ship and easy remove in case of maintenance. The module should be certifiable from classification societies, meaning that safety level should comply with IMO SOLAS. For this reason, the module should be provided with sensors (voltage, hydrogen leak), alarms and integrated ESD procedures. In order to have a higher level of safety, the L2 box could be designed to be gas tight or not.

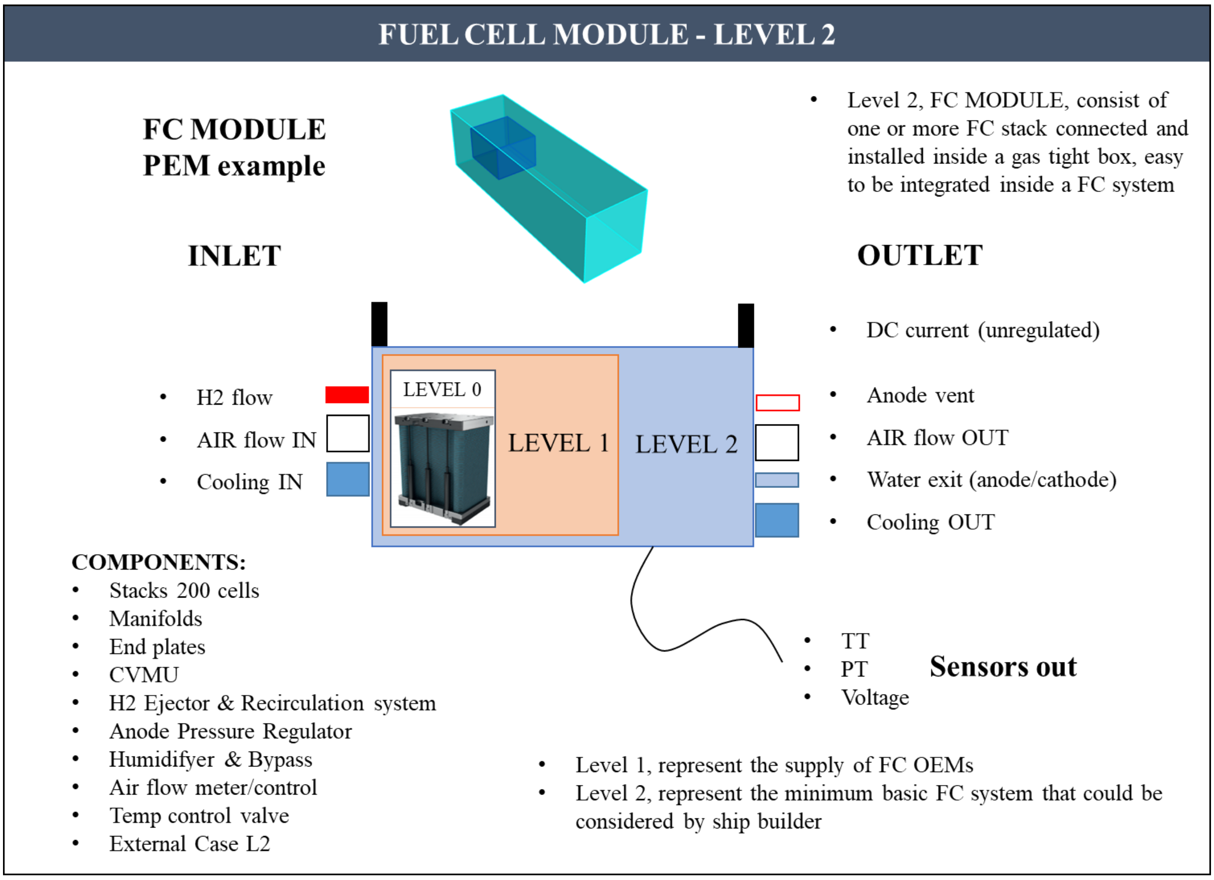


Figure 57. Level 2 fuel cell module

Since a proper guide rule for the installation of fuel cell on-board ships is not available, the “gas tight” requirement for fuel cell module could be too stringent but it can also ease a lot the L2 integration within the higher integration level. From the analysis of land and marine standards, the use of gas inside close spaces require the avoidance of explosive atmosphere through the use of ventilation or by the use of gas tight enclosure with overpressure of inert gas (nitrogen).

In the first case the avoidance of the explosive atmosphere is provided by mechanical ventilation at higher integration level or at the fuel cell space level. In the second case, the mechanical ventilation of the fuel cell space could be reduced or activated only in emergency case, highly reducing the BoP energy consumption. The L2 configuration with gas tight enclosure will be indicated as *"gas safe"*.

- ***Level 3 (L3).*** From the market analysis the standard L1 power size of 30 kW has been found, together with higher power L1 module made of single or more stacks up to 200 kW power. As average, L2 fuel cell module could be considered between 30 to 100 kW power range. In order to reach MW power ranges required by ships, many modules should be connected together. Following the "modularity" property of the fuel cells and considering the "redundancy" principle of marine systems, an intermediate integration level between the fuel cell module and the fuel cell installation has been created. L3 was defined as ***"Fuel Cell Power System"*** or "fuel cell rack". Due to the compact dimensions of L2 modules, the same philosophy of large battery systems has been followed and racks with the dimension of power electronic shelf has been considered as external case for the assembly of L2 modules inside the L3 fuel cell power system. The former has been thought to be designed such as to be an independent power system, able to provide conditioned air flow, fuel, cooling, auxiliary electrical power to the fuel cell module as well as to collect the module exhausts (air, condensed water and anode purges). Depending on the L2 module power, the L3 fuel cell rack could range between 100 to 400 kW power. Figure 58 shows a scheme of integration with the distribution of the BoP components among the integration levels. The external case of L3 could represent an element of discussion for the rule makers. The same argument addressed to L2 module is faced for L3, either to have a *"gas safe"* L3 enclosure or not. The fuel cell rack represent the last level of fuel cell integration that permit the restriction of possible gas losses caused by malfunctions of ruptures inside a well defined border, the rack enclosure. Otherwise the mechanical ventilation of the whole fuel cell space represents the obliged mean of protection from the formation of explosive atmosphere. The ventilation energy consumption increase with the increasing volume of the ventilated space. Moreover, a small well designed box would be ventilated in a more efficient way than a larger room. Again, to indicate the capability of L3 box to hold possible gas leakage, the *"gas safe"* label will be used.

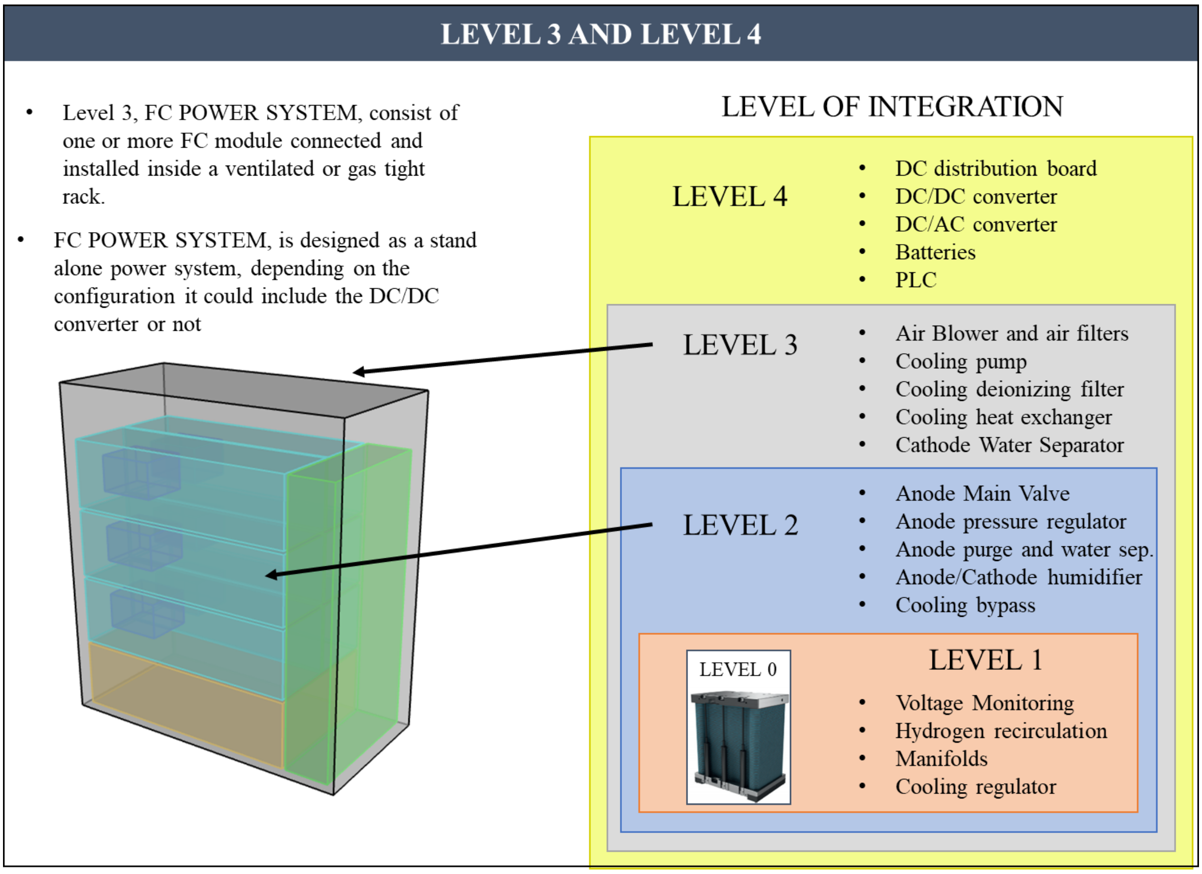


Figure 58. Level 3 fuel cell power system

- ***Level 4 (L4).*** The last integration level is the ***"Fuel Cell Power Installation"***. The term has already been used by various classification societies inside their own fuel cell guidelines (83). The same is also present inside the draft of Part E of the IGF code to define the fuel cell power plant able to supply electrical power to the ship. Some classification societies provide a difference between system dedicated to the furniture of electrical power to auxiliary systems only and systems used to power the ship propulsion. This distinction was not considered since SOLAS already give different prescription for generators dedicated to power auxiliary systems and generators dedicated to propulsion. L4 consider all the BoP components excluded by the previous level since are not considered peculiar of the fuel cell power system but are considered as auxiliaries required to the integration on-board the ship. Among the components of L4 there are all the electric power conditioner required. Depending on the ship electric distribution characteristic, a traditional DC/AC converter could be considered after the DC/DC converter as well as the unique presence of the DC/DC, in the case of a modern DC distribution system. The L3 cooling system require a primary cooling loop that could use see water. On the base of the ship power operational profile, batteries will be required to manage pick power control. Finally, the Programmable Logic Controller required to control the system will be required. The fuel cell power installation will be provided with active and passive safety system to reduce the explosion and fire risks. Figure 59 shows an example of a PEM FC power installation.

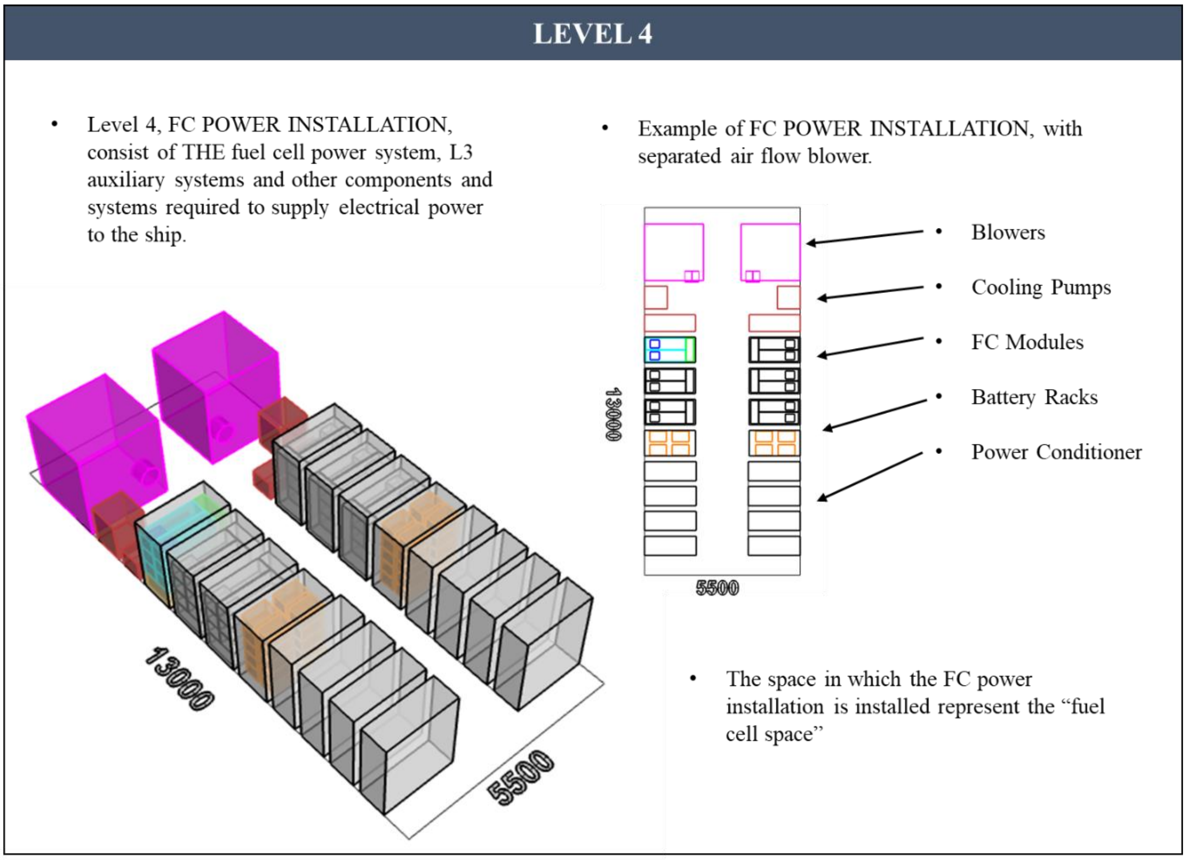


Figure 59. Level 4 fuel cell power installation

Conclusion

A general FCS architecture considering PEM fuel cell and hydrogen storage was given. A similar configuration could also be used for other fuel cell types, but the presence of fuel processing unit would require a more detailed analysis. In the following paragraph, a tentative terminology for the FCSs is given considering any kind of fuel cells and storages, also considering the presence of a fuel processing unit. The reason why a hydrogen fuelled PEM FCS architecture has been specifically developed derives from the previous analysis on the performances of alternative fuels, but, as demonstrated in Chapter 2.1, the use of PEMFC don't exclude the possibility to use primary fuel (fuel different from hydrogen). Moreover, the thermal compatibility between low temperature fuel cell and the processing unit, whatever the primary fuel adopted, is not possible. For this reason the fuel reformer could be considered as a separate unit with respect to the FCS. In this case, the presented FCS architecture would remain unchanged. Per contrast, HTPEMFC and SOFC are able to be coupled with fuel processing unit. In particular the following configurations (Table 46) have been found to be attractive for marine applications. These cases favour the use of integrated reformer that would require a different FCS architecture.

Fuel Cell Stack	FC fuel	Primary Fuel	Reformer coupling
PEMFC	Hydrogen	hydrogen	no need
HTPEMFC	H2 Syngas	Methanol	yes
SOFC	Methane	LNG	yes

Table 46. FCS and fuel favourable configurations

In the following some real examples are reported in order to show the corresponding available market products. As said, at the present there aren't specific marine fuel cell solution, but the modularity concept has been developed for land based power plant up to MW power ranges. Some solution are ready to be adapted to the marine environment and more important are able to fit perfectly into the FCS architecture that have been proposed.

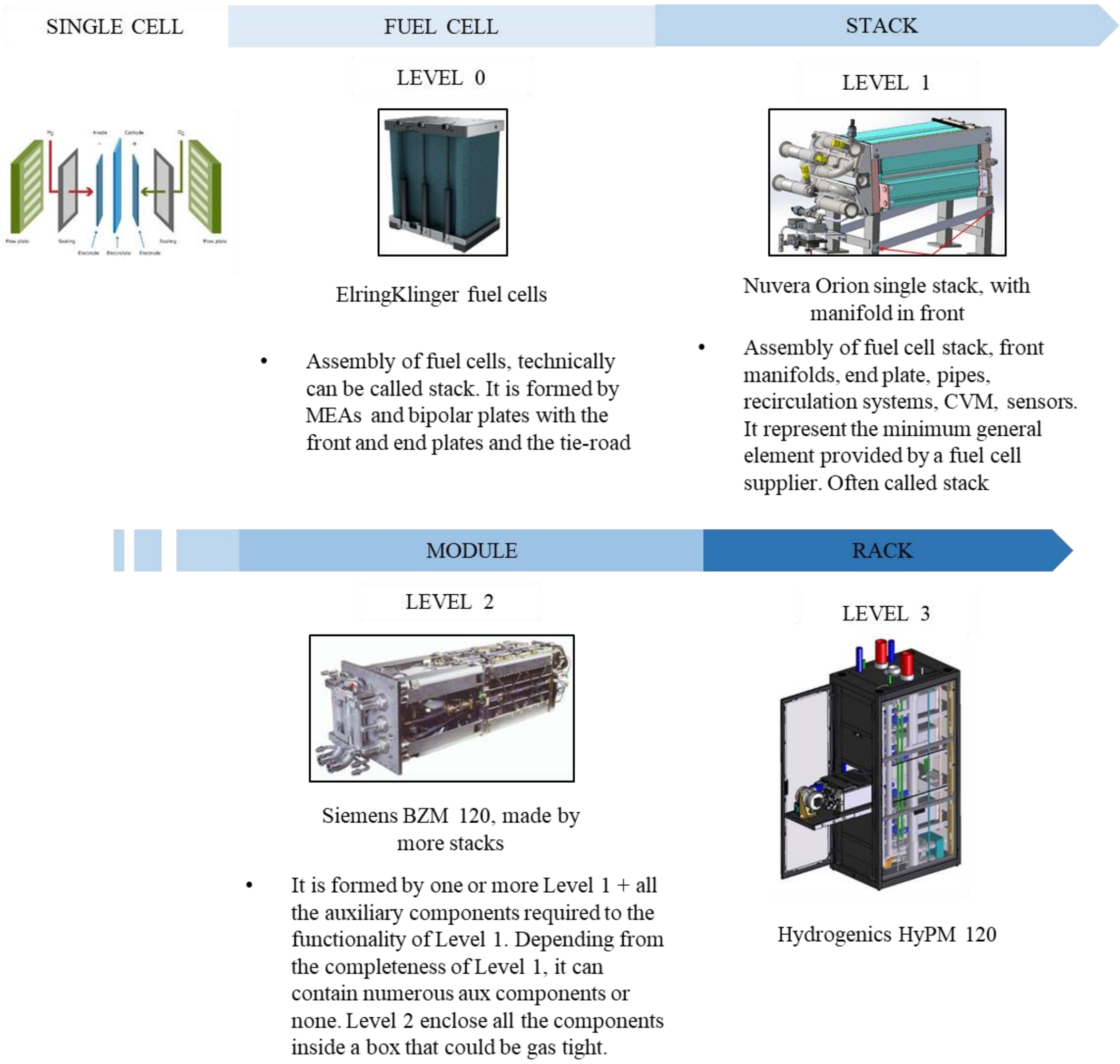
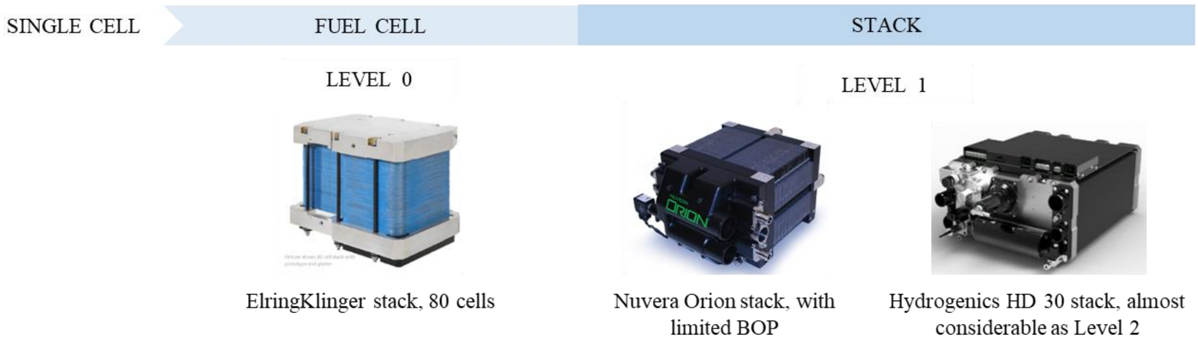


Figure 60. Comparison between level hierarchy and products available on the market

Figure 60 shows the difference between the levels. The fuel cell module in particular, has been thought taking as example the most famous and successful marine application of fuel cells, the Siemens BZM module installed onboard the U212 submarines of the Italian and German Navy. The module differ from the commercial ones available in the market and correspond to the description of Level 2 module. It is not gas tight since is installed inside a *"gas safe"* a L3 fuel cell power systems.



- Other commercial example of fuel cell systems available on the market are given.
- A differentiation between Level 1 (Stack) and Level 2 (Module) is presented. Sometimes Level 1 could correspond to Level 2. The reason of this differentiation comes from integration purpose: Fuel Cell OEMs deliver Level 1 components, that could be supplied with different level of auxiliary systems integrations. Ship builders start to consider the installation of Level 2 or better Level 3 components

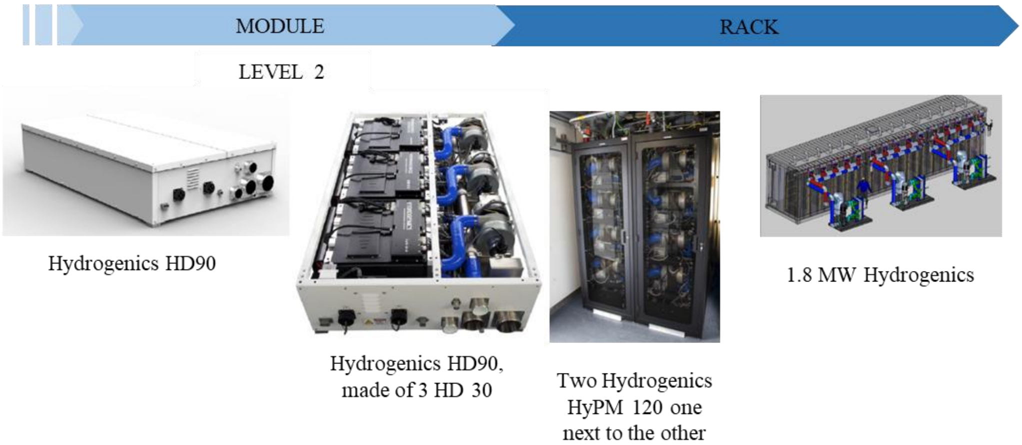


Figure 61. Example of commercial products availability

Figure 61 shows other commercial examples of fuel cells stacks, modules and racks. It is possible to observe the difference between Level 1 supply of Hydrogenics and Nuvera. The first correspond to the basic definition of L1 while the second is highly complete such as it could be almost considered as a L2. To comply with L2 requirements though, the HD30 stack should respond to marine requirements first. Moreover a second example of a almost complete example of L2 fuel cell module is given by the HD90 module of Hydrogenics. The former has a maximum power of 99 kW and is made of 3 stacks of 33 kW power each, it represent an example of a high power fuel cell module. Finally, the HyPM 120, again provided by Hydrogenics, represent a perfect example of a L3 fuel cell power system. As Figure 62 shows, the module is made by 4 HD30 stacks, each of which is provided with it’s own blower. The rack is completed with all the fluid and electric connection and controls. The HyPM 120 is used to design large fuel cell power plant as the 1.8 MW. The design example shows the integration of more L3 racks in a unique system with the cooling pumps and pipes on the front, that should correspond to part of L4 auxiliary system together with the electric power conditioning.

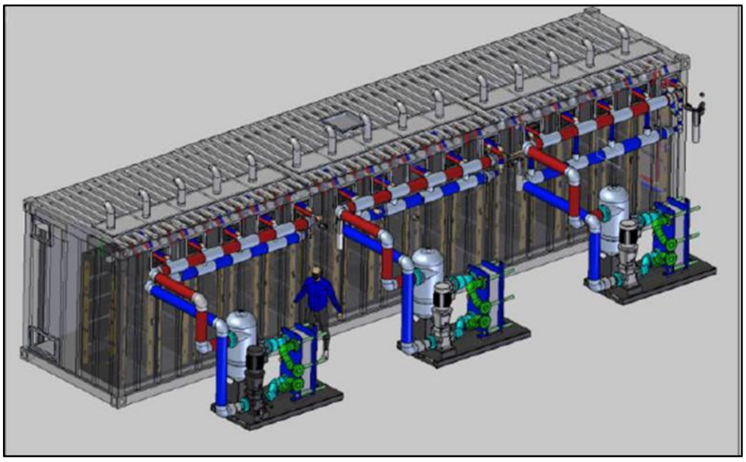



Figure 62. L3 land based system example

2.4.3 FCS terminology

The importance of terminology is highlighted. From the definition of the system components depend the system design and rule definitions. In the following will be presented a tentative definition of the main fuel cell components, defined on the base of the definition made by classification society's guidelines, IMO IFG Part E draft code, IEC standards (e.g. IEC 60079 series, Explosive atmospheres and IEC 60092-502, Electrical Installations in Ships – Tankers – Special Features).

- *Fuel Cell (L0).* A fuel cell is an electrochemical cell that converts the chemical energy from a fuel into electricity (DC), heat and reaction products through an electrochemical reaction of hydrogen rich gas fuel with oxygen or another oxidizing agent.
- *Fuel Cell Stack (L1).* Assembly of fuel cells, separators, cooling plates, manifolds, end plate, recirculation system, control voltage monitor system and supporting structure. It contains element supplied by FC OEMs.
- *Fuel Cell Module (L2).* Assembly of one or more fuel cell stacks (Level 1 components), systems and means for monitoring and/or control of the fuel cell stack. It contains the components inside an enclosure that can be gas tight (labelled as *"Gas Safe"*) or not. If a Fuel Processing unit is connected to the stack, it becomes the *Combined Fuel Processing and Fuel cell Module*.
- *Fuel Cell Power System (L3).* Assembly of one or more fuel cell module (Level 2 components). Contain the following subsystems: fuel cell modules, oxidant processing system, fuel processing system, thermal management system, water treatment system, power conditioning system and their control systems. It contains the components inside an enclosure that can be gas tight (labelled as *"Gas Safe"*) or not.
- *Fuel Cell Power Installation (L4).* Is composed by one or more fuel cell power systems (Level 3 components) and other components and systems required to supply electrical power to the ship.
- *Fuel cell space.* Is the space containing elements of the fuel cell power installation.
- *Fuel processing unit*. System that converts the primary fuel as stored on-board the ship into FC fuel suitable for operation in the fuel cell.
- *Fuel processing installation*. Is composed by one or more fuel cell processing unit and other components and systems required to supply fuel gas to the fuel cell power installation.

- *Fuel processing space*. Is the space containing elements of the fuel processing installation.
- *Primary Fuel.* Can be gases or liquids, for instance methane or natural gas, methanol, propane or diesel, hydrogen. The primary fuel is stored on-board the ship and can be classified as FC fuel if it can be directly fed to the fuel cell.
- *FC Fuel.* Is the fuel fed to the fuel cell. Depending on the fuel cell technology can be hydrogen, hydrogen rich gas, methane, methanol.

2.5 Conclusions

In any case their future marine use aboard ships will be surely start in conjunction with ICE rather that fuel cells. For this reason, the combination between LNG, LPG or Methanol with reformer and fuel cells or directly with fuel cells cannot be considered a real alternative to the fulfilment of IMO SOx and NOx emissions limitations. NOx emission reduction though is not a sufficient condition to switch from ICE to fuel cells, neither the reduction of noise and vibrations.

On the contrary, the future presence of these alternative fuels on-board ships will promote the use of fuel cells on this ships since one of the largest obstacle to fuel cell introduction, fuel storage, would have been already solved.

From the fuel cell SOA analysis, other limitation have been found concerning power size mainly, that together with costs and fuel storage limit the introduction of this technology in the maritime sector. For this reason fuel cell systems will be considered able to power APUs dedicated to AUX systems and low speed operative conditions on-board ships, at least during the short-medium term. The union of these two statements, namely LNG,LPG and Methanol performance with ICE and fuel cell systems power limitations, together with the above considerations, brought to the following:

- LNG, LPG and Methanol are able to substitute FO completely as well as to permit the compliance of IMO ECA emission limitation if used inside ICE equipped with EGR or SCR.
- Hydrogen, whatever the energy medium (CH2, LH2, MH) is effective only in conjunction with fuel cells.
- LNG, LPG and Methanol do not represent an alternative solution to the IMO ECA emission limitation compliance due to the less expensive ICE solution.
- Hydrogen could represent an alternative solution to the IMO ECA emission limitation compliance as APU.

3. Simulation Models

The FCS and the hydrogen storage system assessments would have been ineffective without a direct technology performance experience and analysis. The former would have been impossible without laboratory tests and simulation model respectively.

Simulation models have been developed from the beginning of the PhD studies as an important instrument to better understand the fuel cell functioning. Later on, the models have been flanked by laboratory tests with small FCS (Ballard Nexa 1200 and Nuvera Power Flow 5000), that gave the possibility to validate the simulation models (84). But two important variables were missing:

- Simulation and experimental test of hydrogen storage systems
- Marine integration of FCS

Fuel cell marine applications require the integration of the FCS with the ship systems (power conditioning, control, cogeneration, storage systems and so on). Moreover, ships require MW size power systems that have different technical problems from 1.2 or 5.0 (kW) ones. For these reasons, the model simulation has been used to:

- Simulate the behaviour of hydrogen storage system
- Simulate the FCS coupling with the BoP and the ships systems

The development of a new FCS simulation model with the goal to assess the coupling of more fuel cell modules with the electric power conditioning systems, the liquid cooling systems, the air blower unit/units, control logic and the hydrogen storage system was launched. Simultaneously a new fuel cell laboratory (the HI-SEA Joint Laboratory (62)) for the validation of the simulation model was developed. Both are under construction and represent the future development of the PhD studies.

In order to complete the system analysis a simulation model and test rig for the development of a Metal Hydride hydrogen storage system has been made. A first FCS simplified model based on the experience of the previous model on the Ballard Nexa was built, in order to assess the possibility to thermally couple the fuel cell with the metal hydride hydrogen storage system. The model was used to correctly size the MH test rig that will be used to validate the MH simulation model.

In the following simulation model, built using the Simulink environment, is presented:

- the Metal Hydride simulation model designed to assess the performance of MH2.

The reason why the MH system has been chosen as storage system for analysis rely on the positive results of the sailing boat project (H2Boat) and the mega yacht project conducted together with Fincantieri (MY73 project).

3.1 Metal Hydride Storage Model

The Metal Hydride hydrogen storage system simulation model was developed to analyse the functioning of this particular storage system and to develop a tool able to assist the design of MH storage system for marine applications. The MH simulation will be used to assess a virtual thermal coupling with a large FCS for ship application and to analyse and design a coupled PEMFC-MH storage system for the H2Boat project.

3.1.1 Introduction

In the following, the model of a metal hydride was set in order to simulate hydrogen absorption and desorption processes. Generally, this kind of computer models are broadly described in literature since they are used to a better understanding of the metal hydride behaviour and achieve, for example, rapid charging and discharging rates at moderate operating conditions, and of course high volumetric and gravimetric densities. However, due to the wide variety of metal and complex hydrides, there is still much to find out about the properties of this compounds.

This kind of models are seldom statics. They attempt, indeed, to simulate metal hydride desorption/absorption, often with the target to improve kinetics rate i.e. the process dynamics. Therefore, time derivatives are needed in order to make the mathematical model closer to the actual phenomenon behaviour. Furthermore, for a better understanding of the heat transfer phenomena as well as quantities distribution in the alloy, many models consider also the change of the variables in space, so spatial derivatives. The aim of this work is to set up a simulation model that simulates the metal hydride behaviour in order to compare the results obtained with those present in literature and the data from the experimental tests. In terms of system theory, it is possible to relate this system to a black box system (Figure 63), an abstraction representing a class of concrete open systems, which can be viewed solely in terms of its inputs (stimuli) and outputs (responses), without any knowledge of its internal workings.

Figure 63. A black box typical scheme

It is thus clear how a zero-order simulation model was sufficient to provide results that describe, anyway, the actual behaviour of the metal hydride system with a very good approximation. Moreover, only resorting to the time derivative makes the equation set of the mathematical model, easier to be implemented and solved. However, the one or two dimensions models may help to find out about temperature or pressure distribution throughout the metal hydride system during hydrogen uptake or release.

Generally, the control volume in the physical model, is represented by a closed tank containing the alloy powder. Then, the simulation tries to predict the transient heat and mass transfer in such a system, hence temperature *T*, pressure *P* and concentration *C*. Other parameters are necessary though, as reactor geometry values, hydrogen to metal atomic ratio, rates of absorption/desorption, thermodynamic properties of the metal hydride, etc.

The designing step is essential in order to have a simple model that simulates the system processes as close as possible to the actual phenomena, giving so very reliable output data.

3.1.2 Physical Model

The implementation of a physical model requires some steps, such as the definition of the system and environment or the statement of appropriate assumptions in order to simplify the governing equations so that they can be easily used in the model.

This study is based on the F. Gonzatti and F. Farret work (87), which presents a model of a LaNi5 metal hydride-based hydrogen storage tank to simulate and control the dynamic processes of hydrogen absorption and discharge from a metal hydride.

The system is represented by a composite vessel made of an external tank, which internally comprises seven cylindrical tanks each one containing the same alloy powder quantity (Figure 64). The remaining main external volume accommodates the water circulation for the required heat exchange during the hydrogen absorption or desorption processes.

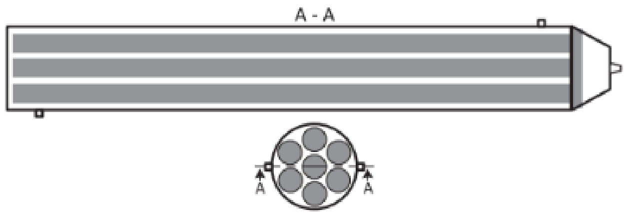


Figure 64. Layout of the metal hydrides tanks in the cylinder

In order to simplify the given system, it was considered only one alloy containing tank with a volume and mass given by the sum of the seven in the original model. This approximation allows to avoid a further increasing of the system complexity without affecting the final results and considerations. The tank with the involving processes are represented in Figure 65. As the image shows, water flow rate, denoted by $\dot{m}_{w,c}$, passes through two orifices placed in the bottom and in the upper part of the storage vessel.

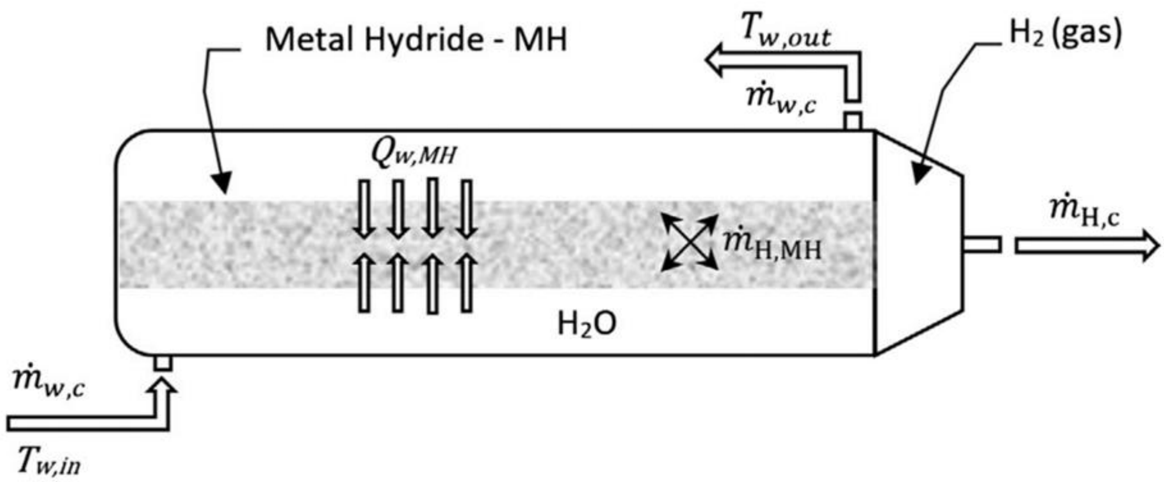


Figure 65. Metal hydride cylinder used in the model

Once the exchange fluid is in contact with the cylinder containing the MH, heat is transferred for both thermal conduction and convection ($Q_{w,MH}$). Depending on the process stage, the heat flow goes from the metal hydride cylinder to water (i.e. exothermal process) if absorption is taking place, whilst $Qw_{,MH}$ is transferred in the opposite direction (as in Figure 65) if hydrogen is being released. Then, gas H2 ($\dot{m}_{H,MH}$) flows into the MH cylinder or outside of it, whereas it is being respectively absorbed or desorbed. The hydrogen flow rate that effectively leaves or enters the tank from or to the outside, is indicated with $\dot{m}_{H,c}$. The metal hydride as well as the water circulation line do not completely fill the tank volume, as it can be seen in Figure 65. The remaining empty volume is indeed, filled up with the H2 gas, which enters or leaves it depending on the type of process. Therefore, hydrogen flow through this volume is driven by two factors: one is represented by the desorption (or absorption) process itself, which releases (pulls away) the gas in this region; the other factor is given by pressure difference between the inside and outside of the external tank, which makes the gaseous element to be transported through the orifice.

However, since several chemical and physical processes take place during hydrogen storage, their translation in mathematical language could not be an easy task. By making some hypotheses it is possible to introduce a certain number of simplifications that make the model still representative of the phenomenon it is describing but easier to implement. Therefore, some preliminary assumption were made (88), that will be used as equation simplification hypothesis:

1. Hydrogen behaves like an ideal gas;
2. The compression work and viscous dissipation is negligible;
3. Radiate heat transfer is negligible;
4. The tortuosity and dispersion terms can be modelled as diffusive fluxes;
5. Both the gas and solid have the same temperature (local thermal equilibrium);
6. The effect of pressure variation (heat transfer by mass convection) is neglected;
7. Quantities variation along radial direction are negligible;
8. Pressure and temperature can be considered constant along axial direction.

Given that, the physical model were transformed into a mathematical one through the definition of the governing equations.

3.1.3 Mathematical Model

During the hydrogen adsorption or desorption process, the P-C-T diagram gives information about three thermodynamic variables, i.e. ***pressure***, ***temperature*** and ***concentration***. Thence, to completely describe the system, three equations are needed at least. Most of the mathematical models present in literature that describe this kind of dynamic systems, define those equations with a ***mass balance***, an ***energy balance*** and a ***reaction kinetics equation***. Usually some other mathematical statements are required in order to determine possible secondary variables, which could lead to an underdetermined system.

The microscopic energy, mass and momentum balance equations are obtained from substitution of relevant fundamental physical, mechanical and thermodynamic laws in the appropriate conservation laws. These are converted to the macroscopic governing equations using the spatial averaging theorem (89), an averaging procedure over a volume to represent the physical reality of the system by the mathematical model (90). The expression for averaging a microscopic quantity ηi over a volume is given by:

$$\eta_i = \frac{1}{\omega_i}\int \eta_i d\omega \qquad (3.2.1)$$

where ω is the averaging volume, η denotes properties such as temperature T, pressure P and density ρ and i designates the phases present (usually the solid and the gas).

In order to define the governing equations of the system, it has to keep in mind that the process behaviour can be completely described by three thermodynamic variables: the pressure, concentration and temperature of the system. Hence, three mathematical expressions are equally necessary.

3.1.4 Heat flow

Because of the strong temperature dependence of the hydriding and dehydriding processes, determining and analysing the temperature profile is essential. For this purpose, energy balance for the MH porous media is obtained from substituting relevant microscopic heat transfer equations for the pore-scale conservation of energy law, which is an extension of the first law of classical thermodynamics. Thus, the general equation of change for internal energy is:

$$\frac{\partial}{\partial t}(\rho U) = -(\vec{\nabla}\cdot\rho U\vec{v}) - (\vec{\nabla}\cdot\vec{q}) + Q - P(\vec{\nabla}\cdot\vec{v}) - \psi_{viscous} \qquad (3.2.2)$$

where U and $\vec{v}$ are the internal energy between two equilibrium states and fluid velocity respectively; ρ is the density, Q is the heat added to or removed from the system through convection or internal sources such as reactions and $\vec{q}$ is heat transferred by conduction. The terms $P(\vec{\nabla}\cdot\vec{v})$ and ψ viscous are compression work and viscous dissipation respectively. These two terms can be neglected for hypothesis 2.

In order to convert equation (3.2.1) to the usual form of energy equation as a function of temperature, U can be rewritten as:

$$U = H - \frac{P}{\rho} \qquad (3.2.3)$$

Where H is the enthalpy. Now, substituting (3.2.3) in equation (3.2.2) and applying the material derivative, gives:

$$\rho\frac{DH}{Dt} = -(\vec{\nabla}\cdot\vec{q}) + Q + \frac{DP}{Dt} \qquad (3.2.4)$$

Moreover, enthalpy can be expressed as a function of temperature and pressure:

$$\frac{DH}{Dt} = c_P\frac{DT}{Dt} + \left(\frac{1}{\rho} + \frac{T}{\rho^2}\frac{\partial\rho}{\partial T}\right)\frac{DP}{Dt} \qquad (3.2.5)$$

Where CP is the specific heat capacity.

Therefore, by substituting the (3.2.5) into the (3.2.4) the energy equation is obtained:

$$\rho C_P\left[\frac{\partial T}{\partial t} + \vec{v}\cdot\nabla T\right] = \lambda(\nabla^2 T) + Q - \frac{\partial\ln(\rho)}{\partial\ln(T)}\left(\frac{\partial P}{\partial t} + \vec{v}\cdot\nabla P\right) \qquad (3.2.6)$$

With λ that is the thermal conductivity of the material. Moreover, $\frac{\partial \ln(\rho)}{\partial \ln(T)} = 1$ for an ideal gas (hypothesis 1.)

Energy balance can be expressed for the gas and solid phases separately for a geometry with cylindrical symmetry and with the assumption of neglecting pressure variation:

$$\varepsilon \rho_g c_{P,g} \frac{\partial T_g}{\partial t} = \varepsilon \lambda_g \nabla^2 T_g - \rho_g c_{P,g} \vec{v} \cdot \nabla T_g + H_{g,s}(T_g - T_s)A - m c_{P,g}(T_g - T_s) \quad (3.2.7)$$

$$(1-\varepsilon)\rho_s c_{P,s} \frac{\partial T_s}{\partial t} = (1-\varepsilon)\lambda_s \nabla^2 T_s - H_{g,s}(T_g - T_s)A - m[\Delta H + c_{P,s}(T_g - T_s)] \quad (3.2.8)$$

where A is the solide-gas exchange area, λ is the thermal conductivity and m is the amount of absorbed or desorbed hydrogen per unit volume and unit time, ε is the porosity of the MH bed and H_{gs} is the interphase heat transfer coefficient between gas and solid.

For both phases, the mechanism of heat transfer include heat conduction (λ∇2T), natural convection between gas and solid ($H_{gs}(T_g\text{-}T_s)A$) and the changes in molecular energy ($m \cdot c_{Pg}(T_g\text{-}T_s)$). Heat transfer due to gas motion is taken into account with the term ($\rho_g c_{P,g} \vec{v} \cdot \nabla T_g$) in equation (3.2.7) while the enthalpy changes of the hydriding and dehydriding reactions (m·ΔH) are applied in (3.2.8).

3.1.5 Mass balance

To identify hydrogen concentration distribution in the MH bed and its evolution as a function of time, it is necessary to include mass balance. The equation of continuity, which is obtained from the conservation of mass, expressed by:

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{v}) = 0 \quad (3.2.9)$$

The mass balance for the gas (hydrogen) is:

$$\varepsilon \frac{\partial \rho_g}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(r \rho_g u_r) + \frac{\partial}{\partial z}(\rho_g u_z) = -\dot{m}' \quad (3.2.10)$$

Where u_r and u_z are component of the velocity vector with respect to the radius r and axial z direction respectively. The mass balance for the solid (metal hydride) is:

$$(1-\varepsilon)\frac{\partial \rho_s}{\partial t} = \dot{m}' \quad (3.2.11)$$

where m is the amount of absorbed or desorbed hydrogen per unit volume and unit time and this indicates the reaction rate for absorption and desorption.

3.1.6 Equilibrium properties and reaction kinetics

The mass flow rate per unit volume (m) is defined basing on the rate flaw for hydrogen uptake and discharge reactions and shows a relationship between the reaction rate and species concentrations. To determine such a relationship for each system, experimental works are needed (91)**Errore. L'origine riferimento non è stata trovata.**. Supper et al. (92) and Suda et al. (93) conducted experiments for hydriding some intermetallics such as LaNi5 and MmNi5. The following equations were based on those results to model heat and mass transfer for AB5 systems by Mayer et al. (94).

$$\dot{m}'_{H,MH} = -C_a exp\left(-\frac{E_a}{RT_{MH}}\right) ln\left(\frac{P_{MH}}{P_{eq}}\right)(\rho_{ss} - \rho_s) \qquad (3.2.12)$$

$$\dot{m}'_{H,MH} = -C_d exp\left(-\frac{E_d}{RT_{MH}}\right)\left(\frac{P_{MH} - P_{eq}}{P_{eq}}\right)(\rho_{ss} - \rho_s) \qquad (3.2.13)$$

Where (3.2.12) is used for absorption while equation (3.2.13) for desorption. Here, ρ_{ss} is the density of the metal-hydride at the end of absorption (saturated density) and ρ_s is the density of the solid without hydrogen. C_a, C_d, E_a and E_d are constant and activation energy for hydrogen absorption and desorption respectively. The reaction constants follow the Arrhenius equation $C \cdot \exp(-E/RT)$ for both absorption and desorption reactions. P_{eq} is the equilibrium pressure of the MH system and it plays a significant role in both absorption and desorption processes. The difference between the equilibrium pressure and the system one is the driving force of the sorption processes. As can be seen from eq. (3.2.12), lower equilibrium pressure for the same system causes increased hydrogen absorption and faster formation rate and similarly a higher equilibrium pressure for the same system pressure enhances the desorption (as in eq. (3.2.13)). Thence, because of the direct relationship between temperature and equilibrium pressure, cooling the system during absorption and heating during desorption, helps to increase the reaction rates. Therefore, in addition to the importance of thermal management in MH tank design to achieve the most appropriate P_{eq}, using the most accurate expression for the equilibrium pressure is also necessary (88)**Errore. L'origine riferimento non è stata trovata.**.

$$ln\left[\frac{P_{H_2}}{P_0}\right] = \frac{\Delta H^o}{R} \cdot \frac{1}{T} - \frac{\Delta S^o}{R} \qquad (3.2.14)$$

The Van't Hoff equation (3.2.14) relates equilibrium pressure (P_{eq}) to the absolute temperature (T_{MH}) of the hydride, the change in enthalpy (ΔH) and entropy (ΔS) at a particular uptake (H/M) which is usually taken to be central along the plateau. The values of the change in enthalpy and entropy are a constant for a particular material provided the same reference point (in this case the same H/M value) is used. However, at different H/M values, different values for the entropy ΔS necessitate a modification of the Van't Hoff equation in order to express the dependence of equilibrium pressure on different values of the H/M. The determination of the precise equilibrium pressure is then given by:

$$P_{eq} = f(H/M) exp\left[\frac{\Delta H}{R}\left(\frac{1}{T} - \frac{1}{T_0}\right)\right] \qquad (3.2.15)$$

where $f(H/M)$ is the equilibrium pressure at the constant temperature T_0. This relation has been presented in different forms in several papers. The present work is based on the Nishizaki et al. (95) in which a relation is fitted for a PCT based on experimental data that not only relates P_{eq} to both the hydrogen concentration and temperature but also takes into account plateau features such as hysteresis and the slope factor. Hence, equation (3.2.15) can be written as:

$$ln\left(\frac{P_{eq}}{P_0}\right)=\frac{\Delta S}{R}-\frac{\Delta H}{RT_{MH}}+(\phi\pm\phi_0)tan\left\{\alpha_1\pi\left[\frac{\left(\frac{H}{M}\right)}{\left(\frac{H}{M}\right)_0}-\alpha_2\right]\right\}\pm\frac{\beta}{2} \tag{3.2.16}$$

where ϕ represents the plateau slope factor, ϕ_0 is a slope constant and β defines the hysteresis factor. These values are different depending on the metal-hydride composition. The "+" sign indicates absorption and the "-" sign desorption.

3.1.7 Additional equations

In addition to the governing equations it is necessary to implement a certain number of relations needed to determine leftover unknown variables that otherwise would lead to an underdetermined system.

From hypothesis 1 it is possible to resort to the ideal gas equation in order to find the hydrogen gas pressure:

$$P_{H,MH}=\rho_g R_H T_{MH} \tag{3.2.17}$$

With $RH=R/MW_H$ hydrogen specific gas constant. The actual hydrogen concentration change in the metal hydride during the absorption/desorption process, can be calculated thanks to:

$$\left[\frac{H}{H_{max}}\right]=\frac{\rho_s-\rho_{s0}}{\rho_{ss}-\rho_{s0}} \tag{3.2.18}$$

The overall heat transfer between the metal hydride and the water that circulates in the rest of the tank, can be estimated by the following heat balance model.

$$dQ_{w,MH}=UdA\left(T_{w,in}-T_{MH}\right)=-\dot{m}_w c_{P,w}dT \tag{3.2.19}$$

Integrating the previous equation previous equation with the assumption of uniform metal hydride temperature (hypotheses 7 and 8), yields to the definition of the outlet temperature of the circulation line.

$$T_{w,out}=T_{MH}+\left(T_{w,in}-T_{MH}\right)e^{-\alpha} \tag{3.2.20}$$

where $\alpha=UA_t/\dot{m}_{w,c}c_{P,w}$, At = πDL.

The amount of heat transfer from the circulation water line to the metal hydride can therefore be expressed in terms of the inlet temperature of the circulation water channel.

$$Q_{w,MH}=\dot{m}_{w,c}c_{P,w}\left(T_{w,in}-T_{w,out}\right)(1-e^{-\alpha}) \tag{3.2.21}$$

Finally, applying 7 and 8 hypothesis, namely neglecting the Laplacian of temperature in equations (3.2.6) and (3.2.7), and making some rearrangement, the following equations are obtained in order to describe the physical model behaviour:

Equation	#
$\left(\frac{V_t}{V_{MH}} - 1 + \varepsilon\right)\frac{\partial \rho_g}{\partial t} = \dot{m}'_{H,MH} - \dot{m}'_{H,c}$	(3.2.22)
$(1-\varepsilon)\frac{\partial \rho_s}{\partial t} = -\dot{m}'_{H,MH}$	(3.2.23)
$\left(\frac{V_t}{V_{MH}} - 1 + \varepsilon\right)c_{P,g}\frac{\partial}{\partial t}\left(\rho_g T_{MH}\right) + (1-\varepsilon)c_{P,s}\frac{\partial}{\partial t}(\rho_s T_{MH}) = -\dot{m}'_{H,MH}\Delta H_H + Q'_{w,MH}$	(3.2.24)
$P_{MH} = \rho_g R_H T_{MH}$	(3.2.25)
$\dot{m}'_{H,MH} = -C_a exp\left(-\frac{E_a}{RT_{MH}}\right) ln\left(\frac{P_{MH}}{P_{eq}}\right)(\rho_{ss} - \rho_s)$	(3.2.26)
$\dot{m}'_{H,MH} = -C_d exp\left(-\frac{E_d}{RT_{MH}}\right)\left(\frac{P_{MH} - P_{eq}}{P_{eq}}\right)(\rho_{ss} - \rho_s)$	(3.2.27)
$ln\left(\frac{P_{eq}}{P_0}\right) = \frac{\Delta S}{R} - \frac{\Delta H}{RT_{MH}} + (\phi \pm \phi_0)tan\left\{\alpha_1 \pi \left[\frac{H}{H_{max}} - \alpha_2\right]\right\} \pm \frac{\beta}{2}$	(3.2.28)
$\left[\frac{H}{H_{max}}\right] = \frac{\rho_s - \rho_{s0}}{\rho_{ss} - \rho_{s0}}$	(3.2.29)
$T_{w,out} = T_{MH} + \left(T_{w,in} - T_{MH}\right)e^{-\alpha}$	(3.2.30)
$\alpha = \frac{UA_t}{\dot{m}_{w,c} c_{P,w}}$	(3.2.31)
$Q_{w,MH} = \dot{m}_{w,c} c_{P,w}\left(T_{w,in} - T_{w,out}\right)(1 - e^{-\alpha})$	(3.2.32)
$Q'_{w,MH} = \frac{Q_{w,MH}}{V_{MH}}$	(3.2.33)

Table 47. Equation used in the model

The constant values that were used in the formerly defined equations, are reported in the following tables:

Parameters	Value	Parameters	Value
a	14.15	β	0.3
b	3704.388	ϕ	0.15
α1	1	ϕ0	0
α2	0.5		

Table 48. Eq. (3.2.28) parameters (95)

Where *a* is the ratio *ΔS*/*R* while *b* is equal to *ΔH*/*R*. Other values can be found in Table 49.

Constant	Value
cPw	4186
cPg	14890
cPs	419
Ca	59.187
Cd	9.57
Ea	21179.6
Ed	16420
ΔHm	30478 (adsorp)/30800 (desorp)
ΔHH	1.54·107

MWH	2.01598
P0	101325
U	300
ε	0.5
ρso	8400
ρss	8517

Table 49. MH model parameters

The temperature of the alloy during the absorption or desorption process was found by substituting Eq. (3.2.22) and (3.2.23) into the (3.2.24) which results in:

$$T_{MH} = T_{MH,0} + \int \left[\left(\frac{-\dot{m}'_{H,MH} \Delta H_H + Q'_{w,MH}}{\left(\left(\frac{V_t}{V_{MH}} - 1 + \varepsilon \right) \rho_g c_{Pg} \right) + \left((1-\varepsilon) \rho_s c_{Ps} \right)} \right) - \left(\frac{\left(c_{Pg} \left(\dot{m}'_{H,MH} - \dot{m}'_{H,c} \right) + \left(-c_{Ps} \dot{m}'_{H,MH} \right) T_{MH} \right)}{\left(\left(\frac{V_t}{V_{MH}} - 1 + \varepsilon \right) \rho_g c_{Pg} + \left((1-\varepsilon) \rho_s c_{Ps} \right) \right)} \right) \right] \boldsymbol{dt} \tag{3.2.34}$$

Where T_0 is the metal hydride temperature at the initial time.

The density of the MH was calculated integrating the (3.2.24), achieving the following:

$$\rho_s = \rho_{s,0} + \int -\frac{\dot{m}'_{H,MH}}{(1-\varepsilon)} dt \tag{3.2.35}$$

Being $\rho_{s,0}$ the initial density of the solid. As for the hydrogen gas density, it was derived from equation (3.2.22):

$$\rho_g = \rho_{g,0} + \int \frac{\dot{m}'_{H,MH} - \dot{m}'_{H,c}}{\left(\frac{V_t}{V_{MH}} - 1 + \varepsilon \right)} dt \tag{3.2.36}$$

Where $\rho_{g,0}$ is the gas density at $t=0$.

Thanks to equations (3.2.32) and (3.2.33) was possible to determine the thermal exchange with the environment. With this purpose, it was necessary to determine the area of the heat exchange between the tank and water (A_t). In this model is considered the sum of the values of the seven individual tanks forming the whole cylinder, as shown in Figure 65. The same method was used to determine the total volume of the tanks (V_t) containing the metal hydride. To calculate the volume occupied only by the alloy (V_{MH}), one should take into account the porosity of the material. Then, the equation results in:

$$V_{MH} = \frac{m_{MH}}{\rho_{s0} \varepsilon} \tag{3.2.37}$$

Where $\rho_{s,0}$ is the density of the completely emptied metal hydride.

3.1.8 Initial conditions

After choosing the governing equations and identifying the auxiliary relations, it is necessary to specify appropriate boundary and initial conditions based on the shape and the operating conditions of the reactor and the associated cooling system.

First, it was considered that the alloy and the circulating water through the cylinder are initially in thermal equilibrium, hence $T_{MH}(t=0) = T_{MH,0} = T_w$. Similar considerations were made for the densities of the hydrogen gas and metal hydride. In Table 50 are defined the initial conditions for these quantities.

Initial condition (at t = 0)	#
$T_{MH,0} = T_w$	(4.37)
$\rho_{s,0} = \rho_{s0} + \left\{ \alpha_2 + \frac{1}{\alpha_1 \pi} \left[\frac{ln\left(\frac{P_{eq}}{P_0}\right) - a + \frac{b}{T_{MH}} \pm \frac{\beta}{2}}{(\phi \pm \phi_0)} \right] \right\} (\rho_{ss} - \rho_{s0})$	(4.38)
$\rho_{g,0} = \frac{P_{H,MH,0}}{R_H T_{MH,0}}$	(4.39)

Table 50. Initial conditions

3.1.9 Computer Modeling

Once the set of equations has been defined, it was necessary to implement a simulation model through which it was possible to understand how the system responds to the given input and how it evolve in time. As already mentioned, for this purpose, was used the software Matlab Simulink, a graphical programming environment for modelling, simulating and analysing multi-domain dynamic systems. This software offers an intuitive and friendly user interface through which several tools and options are available.

Figure 66 represents the main screen of the Simulink implemented model. As can be seen, three inputs are connected with the primary block that represent the metal hydride tank, while five output parameters leaves the MH system.

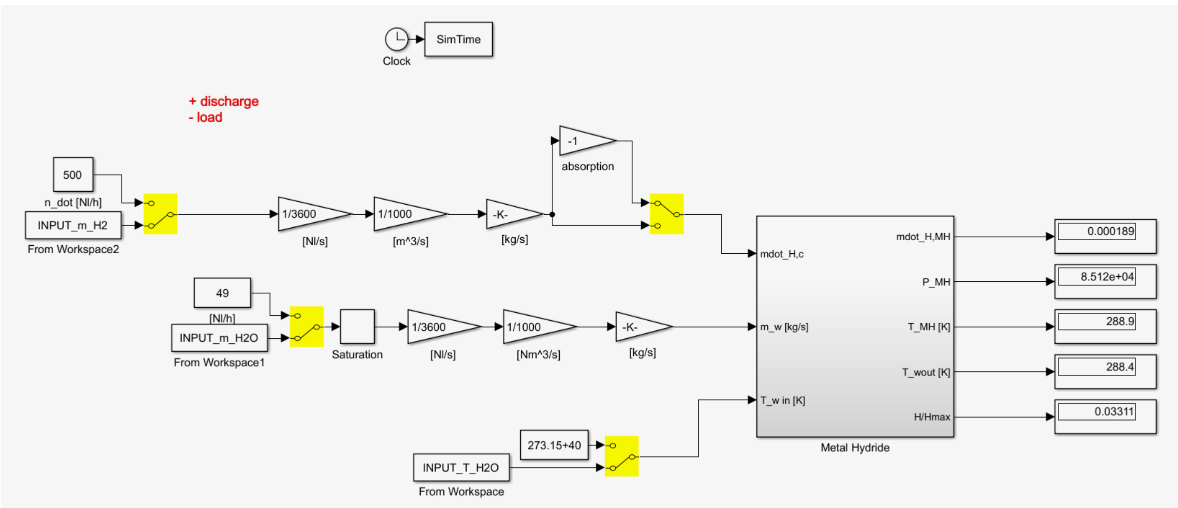


Figure 66. The main screen of the Simulink implemented model

In order to make the model working, three inputs were given: the hydrogen flow rate that enters or leaves the tank ($\dot{m}'_{H,c}$), the heat exchanger cooling volumetric flow rate, water in this case ($\dot{m}_{w,c}$), and the initial cooling flow temperature before the heat transfer ($T_{w,in}$). It has to be noticed that two blocks are present for each one of the three input. This give the possibility to change from the values given by the paper to the test data, in order to compare the simulated results with the experimental values obtained from the experimental tests. Flow rates are given in (Nl·h-1) as the measured data were so sampled, hence it were converted in (kg·s-1).

The model outputs are: the metal hydride temperature (T_{MH}), hydrogen flow rate absorbed or desorbed by the metal alloy during the process ($\dot{m}'_{H,MH}$), internal pressure reached inside the MH (PMH), the temperature of the water that leaves the tank after heat exchange ($T_{w,out}$) and hydrogen concentration into the metal hydride (*H/Hmax*). Moreover, it is possible to display the numerical values acquired by the parameters as well as their behaviour in time thanks to the specific blocks (i.e. display and scope).

The main part of the computer model is represented by the metal hydride block. Here, all the equations set in the mathematical model are implemented. Each one of them represent a subsystem with its own input and output, functions and constants.

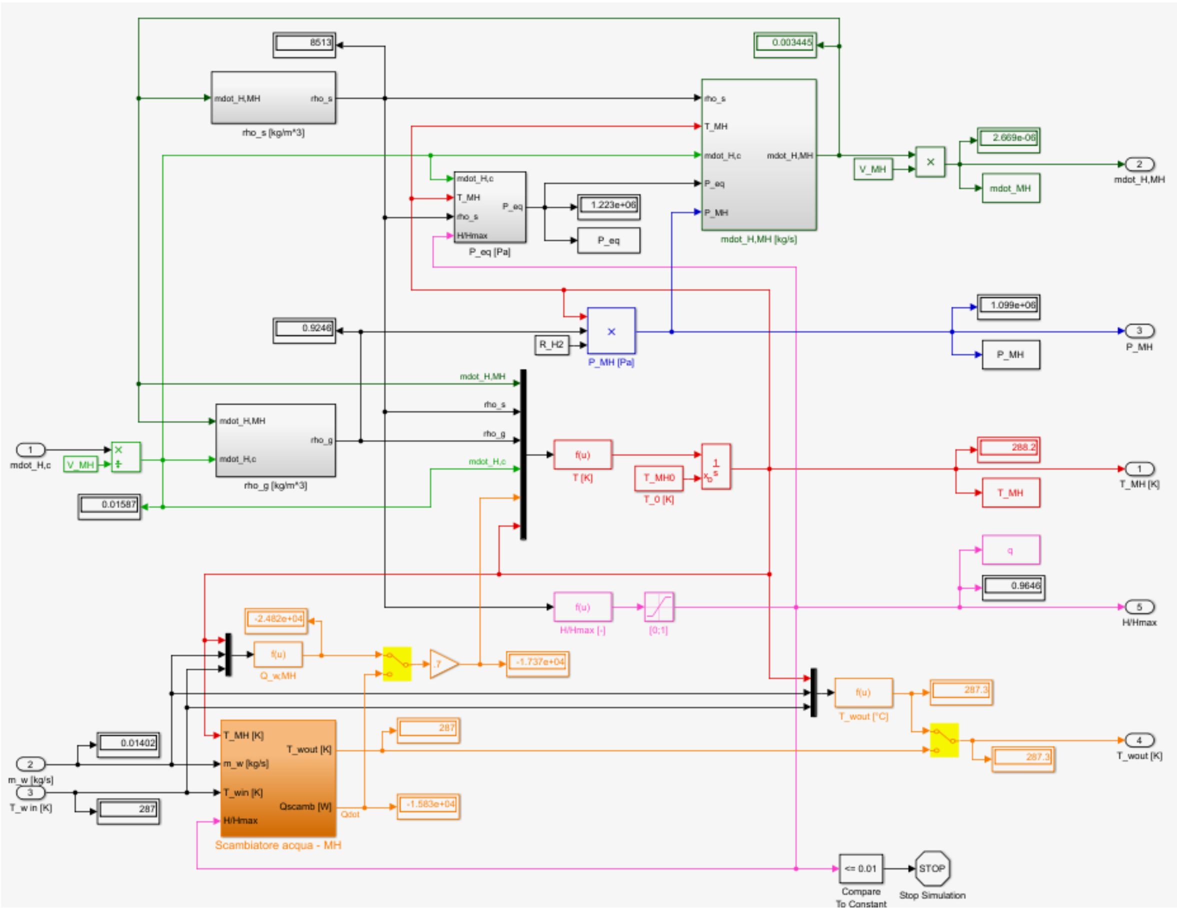


Figure 67. Screen-shot of the simulated MH model

Figure 67 shows the metal hydride subplot with the metal hydride temperature function block (in red) implemented on the basis of equation (3.2.35), while equations (3.2.30), (3.2.31) and (3.2.32) were used to set up the calculation of the heat exchanged between the water flow and the alloy powder (in orange). The hydrogen mass flow rate released or absorbed by the metal hydride was, instead, obtained through the implementation of equation (3.2.26) and (3.2.27) (green in the figure) whereas the P_{MH} block (in blue) uses equation (3.2.25) and, in order to determine the hydrogen concentration in the system, equation (3.2.29) were integrated in the appropriate block. However, other sub-models were implemented in order to compute some parameters that are not outputted but which are present in other equations or influence the behaviour of the calculated variables that the MH block gives in response. These quantities are, for example, the equilibrium pressure or the density of the hydrogen gas and the metal hydride concentration in time.

The model was tested only in steady condition with the goal to assess the capacity to reproduce the performance of determined metal hydride. In particular, a LaNi5 of the AB5 family was successively tested in steady condition and the results were compared. Figure 68 shows a comparison between the PCT curves extracted from the simulation model and the experimental point derived towards the datasheet of the MH tank of Labtech srl, that was used in the MH test rig. The simulation model present a good data overlap especially in the central part of the curve while at the extremes the PCT curve is not well reproduced. The dynamic behaviour is not presented because both the simulation model and the experimental data presented data acquisition limits that did not permit a proper dynamic analysis.

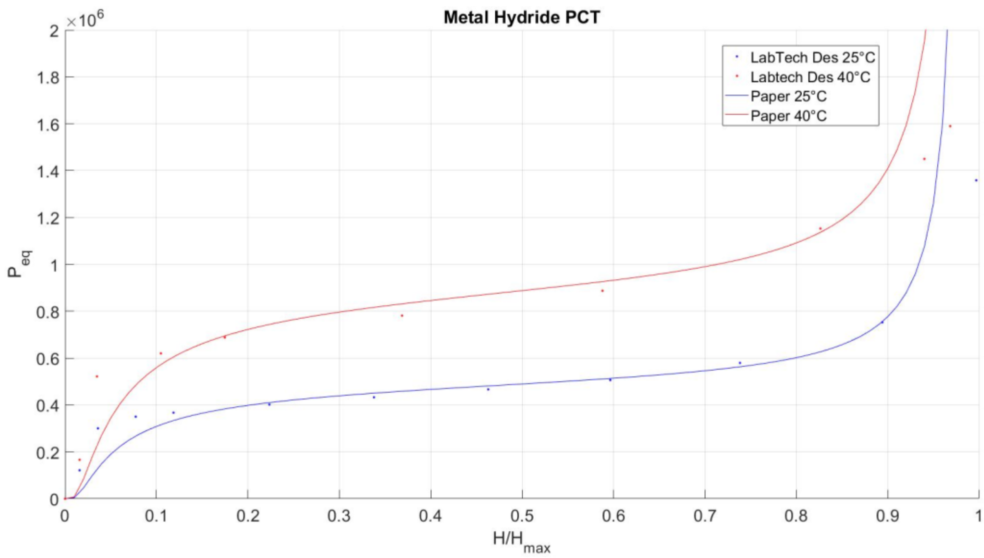


Figure 68. Comparison between experimental PCT data and model values

3.2 Metal Hydrides System experimental analysis

A MH test rig has been designed and built in order to test different kinds of MH systems. The goal was to assess the MH functioning parameters, extrapolate experimental data useful to validate the simulation model and to define the best heat exchange strategy. Three main MH tanks have been identified, characterized by different heat exchange systems:

1. External Heat Exchange
2. Internal Heat Exchange
3. Jacket Tank Heat Exchange

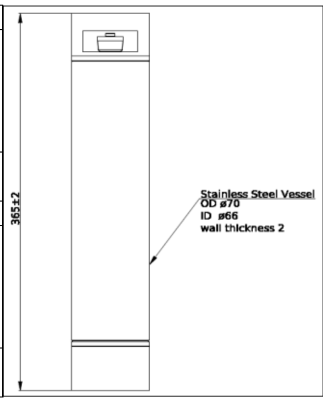
The test rig was initially designed to operate with the first kind of MH tanks. Two MH tanks have been acquired: MH500 with external heat exchange and MH500 with internal heat exchange. Both the tanks are able to store 500 (Nl) of hydrogen. In order to test the third heat exchange configuration a modification on the first MH500 tank will be made.

The test rig has been used to test the first configuration only. After the test were made a data analysis was conducted. The former showed the presence of data acquisition errors related to instrumental noise that didn't permit a confident assessment of the MH performance. The test rig is under development.

3.2.1 Metal hydride tank

The metal hydride powder contained in the tank belongs to the AB5 family, in particular a LaNi5 was used. The former is a very versatile compound, widely investigated and very suitable for hydrogen storage. The nickel-based alloy is commonly prepared by conventional melt casting method, which treats the hydride making it in form of powder in its final state with a particles diameter less than 0.1 (mm) that are stored inside a cylindrical metal tanks. In order to enhance the mechanical and thermodynamic properties, a third element is usually added to the compound by mechanical alloying. In this case, by the addiction of Cerium (Ce), a lanthanide element, allows to reach a higher volumetric density. MH absorb and release hydrogen under thermal cycle. When high temperature are supplied to the MH tanks, the equilibrium (PCT) point is rise to higher pressure levels, for this reason cylindrical tank configuration are used. Table 51 shows the datasheet of the two MH500 tanks.

Hbond 500 External Heat Exchanger				
d	70	mm	0.7	dm
l	365	mm	3.65	dm
H2	500	Nl	41	g
W	5	kg	3.6	kg/l
V	1.4	l		
kg H2/m^3	29.2		kWh/kg	0.28
wt%	0.82		kWh/l	0.98
Hbond 500 Internal Heat Exchanger				
d	80	mm	0.8	dm
l	365	mm	3.65	dm
H2	500	Nl	41	g
W	5	kg	2.7	kg/l
V	1.8	l		
kg H2/m^3	22.4		kWh/kg	0.28
wt%	0.82		kWh/l	0.75



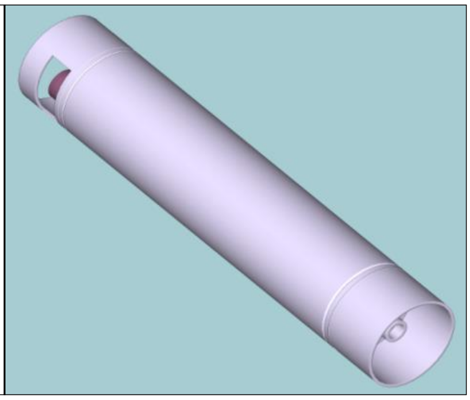


Table 51. MH500 hydrogen storage systems datasheet

The two HBond-500 hydrogen storage systems were manufactured by Labtech Int. Co. Ltd. The maximum hydrogen capacity amounts at 500 (NlH2) (about 0.044 (kgH2)) with a metal alloy mass of 3.3 (kg) whilst the total equals to 5 (kg). The operative conditions at which the hydrogen uptake and release occur, presents an absorption temperature of 25 (°C) and pressure of 15 (barg) while the discharging values are 10 to 30 (°C) and 2 to 10 (barg) respectively. The aforementioned data along with the metal alloy composition are reported in Table 52.

Quantity	Value
Max. Capacity [NlH2]	500
Diameter [m]	
internal	0.006
external	0.07
Length [m]	0.365±0.002
Charging pressure [barg]	15
Charging temperature [°C]	25
Discharging pressure [barg]	2-10
Discharging temperature [°C]	10-30
Alloy composition [%]	
La+Ce	32.1
Ni	67.9

Table 52. Technical specifications of the MH tank

3.2.2 Test-rig

As previously mentioned, experimental tests were made on the metal hydride test rig built using the indication derived by the FCS model. The former gave indication on the required cooling water flow, temperature ranges, hydrogen buffer dimension. Figure 69 shows the P&ID of the test rig that has been designed and constructed inside the laboratory of the Thermochemical Power Group. The test rig was designed to operate with external heat exchange MH500 tank, a particular tank devoid of the internal heat exchanger. The thermal exchange is conducted towards the external surface between the MH and the water in which the tank is immersed. The data acquisition system has been built using Arduino platform.

Figure 70 shows a picture of the final test rig. As the image shows, the MH500 tank was placed into a thermally insulated vessel filled with fresh water, in order to cool or heat the system. Moreover, a pipe system connect the vessel with a water thermal conditioning system, which are alternatively activated in case of absorption or desorption of hydrogen respectively. The hydrogen pipeline has been assembled in a flexible manner, in a way that, according to the kind of process that is occurring, i.e. charge or discharge, it is possible to close or open a certain section of the tube system just by opening or closing a certain set of valves. This strategy permit the use of the same hydrogen flow meter. The former is a hydrogen flow controller equipped with a valve that permit the control of the hydrogen flow that is released of sent to the MH tank in the case. At the end of the hydrogen pipe line a pressure regulator valve has been installed in order to simulate the presence of a fuel cell.

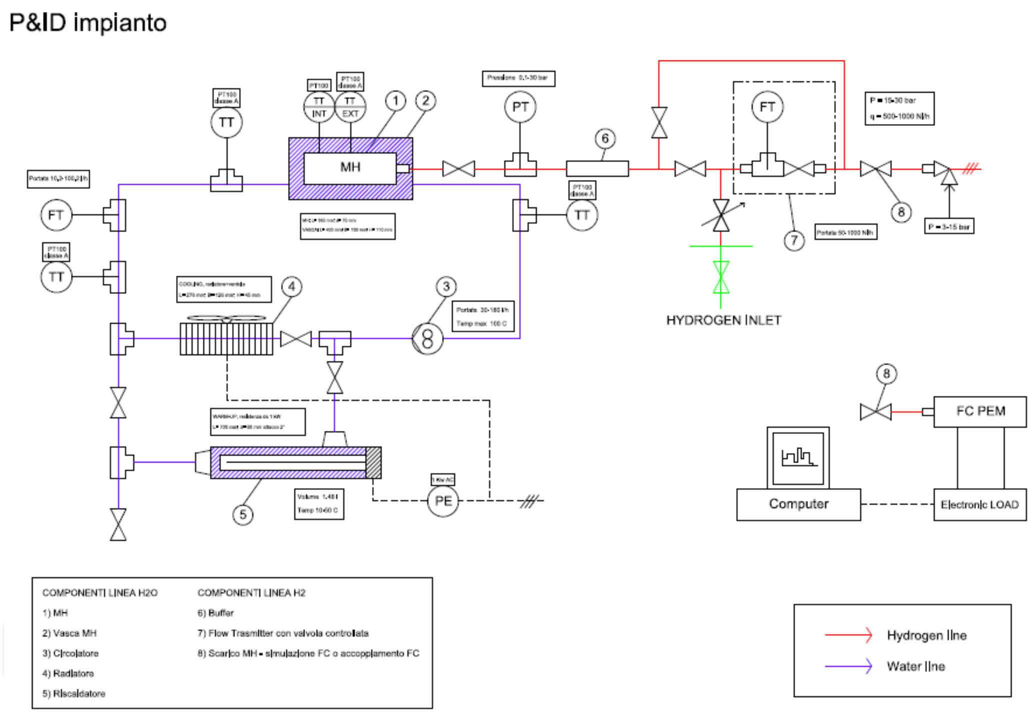


Figure 69 –Layout of the test rig

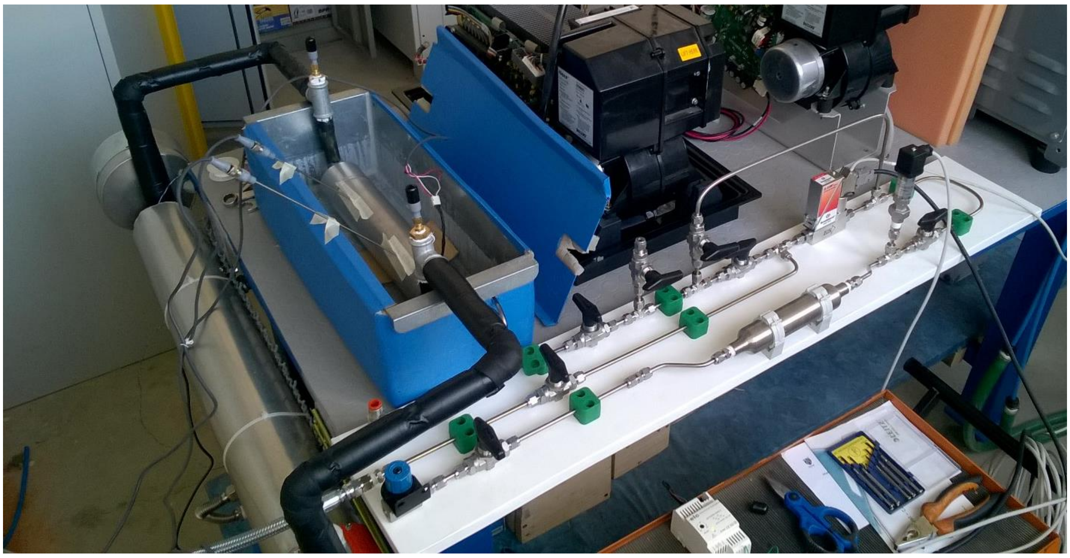


Figure 70. MH Test rig

3.2.3 Charging phase

In the following parts of the results collected during the test campaign on the MH500 with external heat exchange is presented. As already explained, after the data analysis important measure errors where found that did not permit to produce confident explanation of the dynamic behaviour of the system. In particular, temperature measures resulted to be affected by errors during the Analogic to Digital Conversion (ADC). The error that has been made was the experimentation of a new DAQ based on the Arduino controller, which required the use of particular ADC for the PT100 thermo resistance sensors. Unfortunately the printed temperature values presented this problem during fast dynamics, with different grades depending on the number of ACD connected to the controller. For this reason only one series of experimental data has been considered. The former is made by three charging tests and three discharging test operated at steady hydrogen flow of 100 (Nlh).

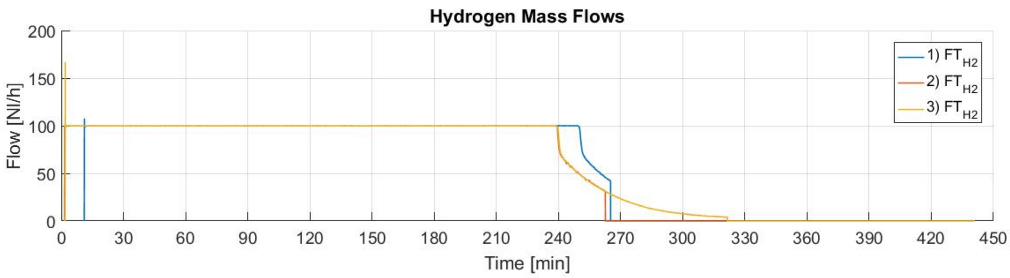


Figure 71. MH Charging Phase - hydrogen flow

Figure 71. MH Charging Phase - hydrogen flowshows the controlled hydrogen flow that has been supplied to the MH500 tank. Three tests (and more, because 20 tests have been conducted but only three are now considered) confirmed the storage tank hydrogen capacity to be of about 400 (Nl) instead of 500 (Nl). This fact is related to two factors: first, the total hydrogen absorbed by the metal hydride could indeed be of 500 Nl but the concentration point could refer to a different loading condition of pressure and temperature; second, the desorption PCT curves indicated in the datasheet refer to a MH sample instead of the tank. The second hypothesis put the measured tank concentration to the effectiveness of the heat exchange. This aspect will be tested toward the analysis of the Internal MH500 tests that have to be made.

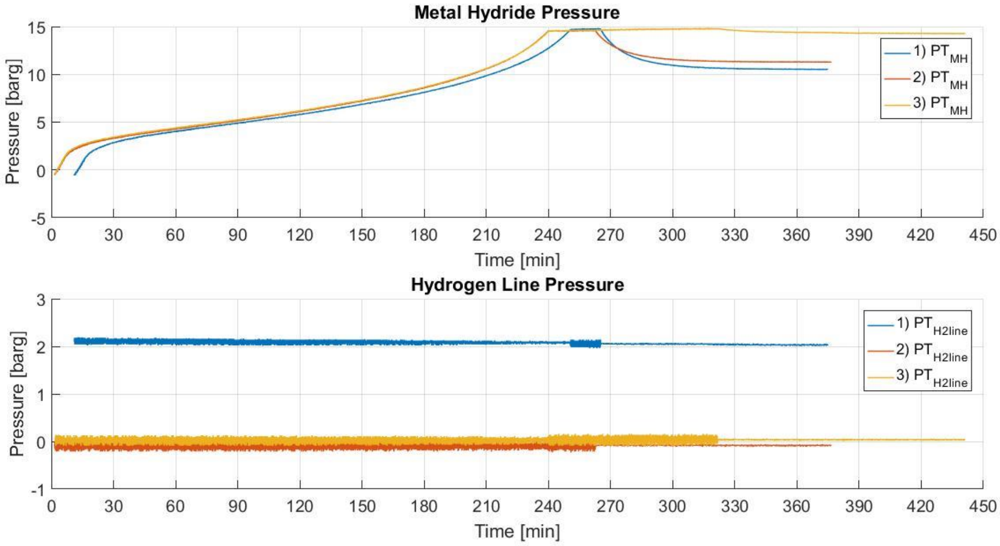


Figure 72.MH Charging Phase - MH and line pressure

Figure 72 shows the pressure trends during the charging procedure. It is possible to see that after four hours the pressure full-scale is reached and the charging procedure is stopped. It is possible to observe that the MH tends to slowly flat to an equilibrium pressure that is lower to the pressure measured during dynamic performance. This aspect is related to two factors: temperature, once hydrogen flow is zero, the absorbing reaction, an exothermic process, tends to slow down and the local temperature decrease lowering the equilibrium pressure; secondly, there is an hysteresis between dynamic and static equilibrium. Both these effects have not been further tested because of the test rig limitations.

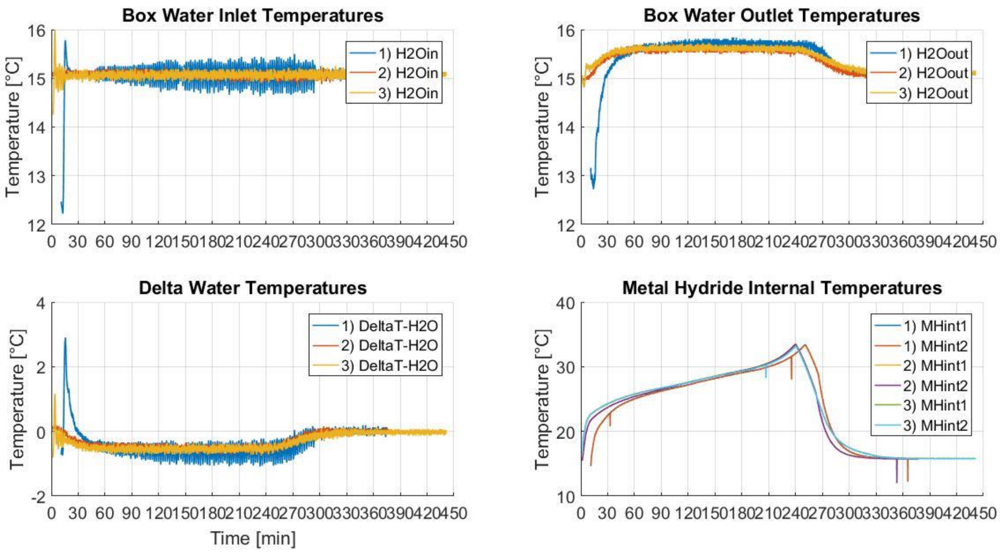


Figure 73. MH Charging Phase - System Temperatures trends

Finally Figure 73 shows the temperature trends. Even if the precise value could be different due to the DAQ problems, the trend can be considered right. It is possible to observe that the test rig control system operated in order to maintain the cooling inlet temperature constant at 15 (°C). The temperature difference between the inlet and outlet cooling water flow is reported, but the noise did not permit to derive a useful information. Using the ΔT it would be possible to evaluate the transferred heat. The Metal hydride temperature follow the expected trends. Future tests will control the temperature conditioning system in order to maintain constant the internal temperature.

A result that is possible to derive is the following. Sea water temperature, considered equal to 15 (°C) is able to permit the charging of this kind of metal hydrides.

3.2.4 Discharging phase

Also discharging test have been conducted, which suffer the same problem related with temperature measurement. Figure 74 shows that three test that have been conducted with equal conditions. It is possible to observe that in one case, the discharge process have been conducted starting from a hydrogen concentration point that was not the maximum one. In this case the hydrogen flow given by the MH500 tank starts to decrease after 150 minutes. For this reason a procedure to enhance the hydrogen desorption was tested, reducing the outlet back pressure initially set at 2 (bara). The operation permit to extract a larger quantity of hydrogen.

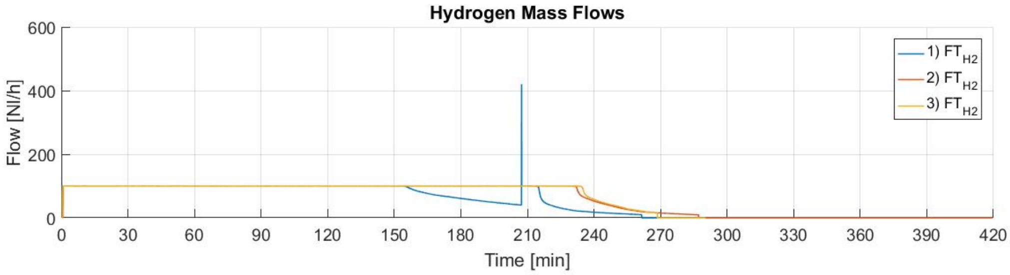


Figure 74. MH Discharge Phase - hydrogen flow

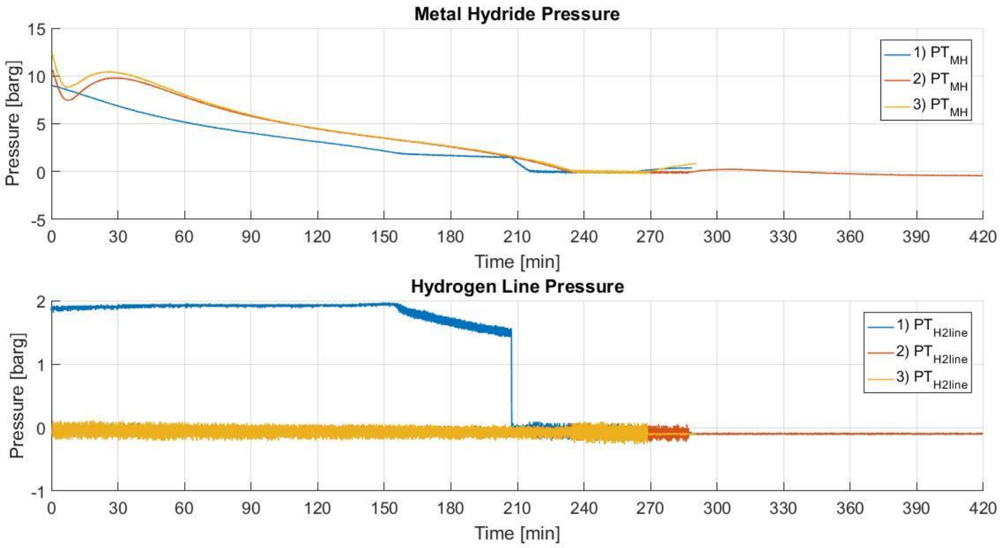


Figure 75. MH Discharge Phase - MH and line pressure

Figure 75 shows the pressure trends inside the MH tank and on the hydrogen pipe line while Figure 76 shows the temperature trends.

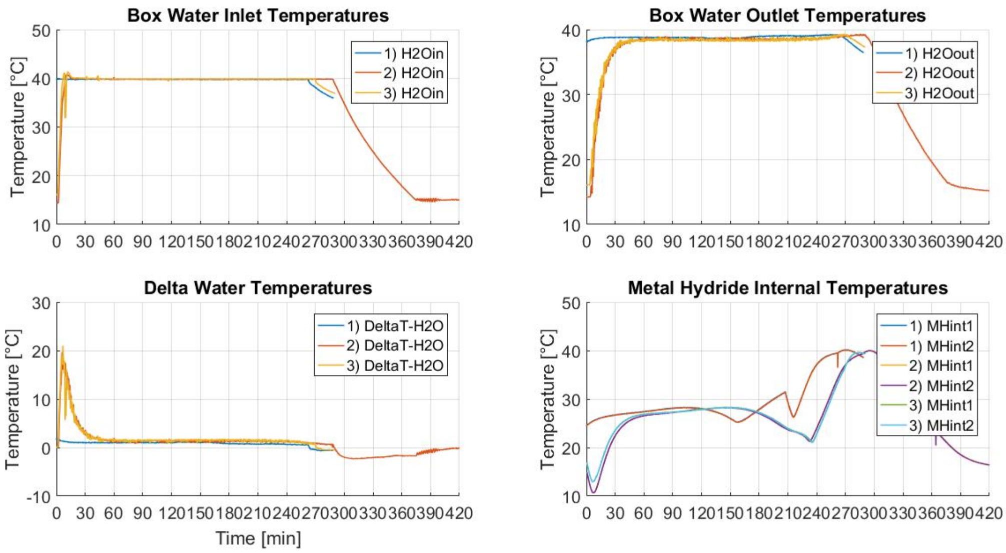


Figure 76. MH Discharge Phase - System Temperature trends

As results, the MH500 metal hydride storage system performance in terms of static behaviour have been analysed. Dynamic tests have been conducted but DAQ limitations did not permit the collection of valuable data. The test rig is under development in order to permit the conclusion of the study.

3.3 Conclusions

During the studies, a MH simulation model was built to analyse the performance, behaviour and control strategies of metal hydrides storage systems. The goal was to thermal integrate the PEMFC with the MH2 system. In order to proceed with a scientific method, a metal hydrides systems test rig has been designed and built. The former has been designed to test different heat exchange MH tanks in order to compare their performance and to collect the data required to the experimental validation of the simulation model. Unfortunately a malfunctioning DAQ did not permit the conclusion of the tests in time. In any case the PEMFC model, combined with the results of the MH model and the experimental results give clear indication that the thermal coupling of PEMFC and MH2 is feasible with a good range margin of success.

4. Case studies and applications

During the long period of study, different occasion to test the applicability of the designed comparative model method and the hydrogen technologies arrived. The analysis of the application projects that have been developed show important information on the market requests and the hydrogen applications. Together they contribute to the enhance of the knowhow and the identification of the obstacles and solutions.

The common characteristic that connect all the projects is the presence of other innovative solutions together with hydrogen technologies. Practically it never happened to simply substitute the ICE and FO with a FCS and a hydrogen storage system on-board a traditional ship design. Due to the characteristics of hydrogen and related technologies, its introduction in shipping has always been considered a driving force to implement other innovation on different sectors as structures, energy system design and others.

4.1 MY75 Project

Figure 77. FC SWATH 75 concept

During 2013 Fincantieri Mega Yacht decided to develop the design of the most luxury and environmental yacht ever. The concept was developed with the goal to offer a smoother ride on-board with a zero emission operative profile in order to permit the entrance inside special emission controlled areas and to give stability and low noise emission in a more efficient configuration while offering comfortable cruising.

The result was the development of a the new Fuel Cell propelled Small Waterplane Area Twin Hull (SWATH) concept: FC SWATH 75, Figure 77.

Many important innovations were introduced within this concept. In the following a short explanation of the project main characteristics are reported in order to show the decision procedures that brought to the choice of a Fuel Cell auxiliary power plant for this ship. Project MY75. Figure 78 shows the drivers that favourite the launch of the project.

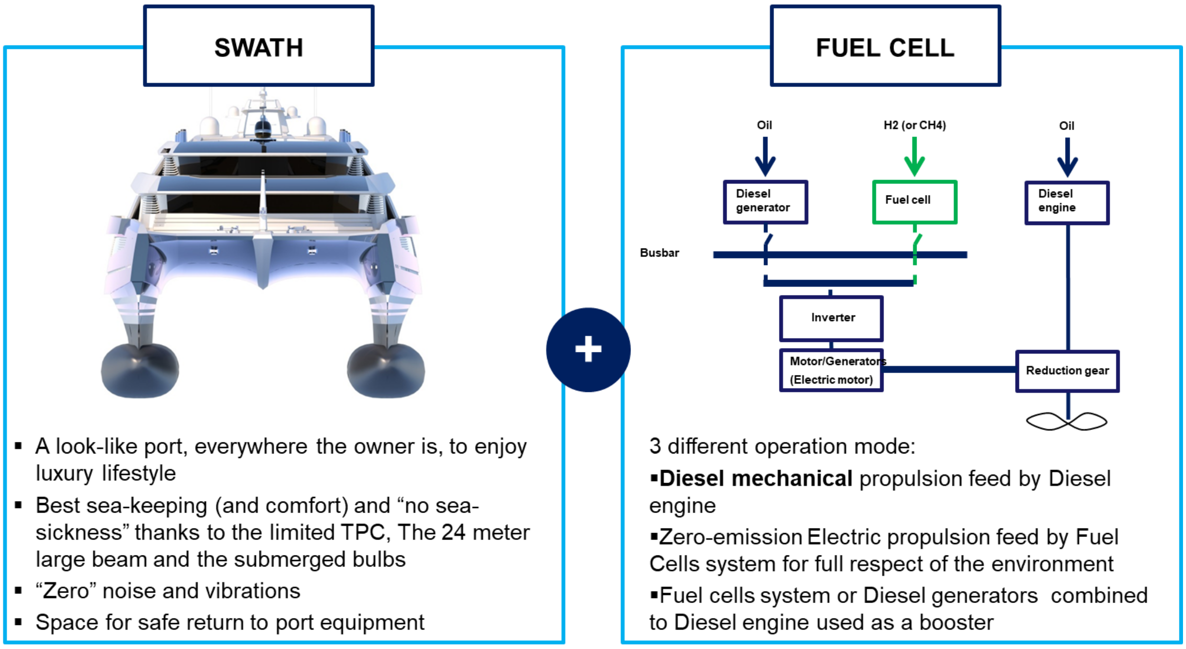


Figure 78. MY75 Project characteristics

In order to define the most suitable FCS, fuel cell and hydrogen storage systems comparative models have been constructed. After the first technology analysis, it becomes clear that the poor hydrogen storage system performance strongly limit the adoption of the fuel cells that on the contrary show good performances compared with ICE. In particular PEMFC were identified as the only technology ready to be installed on-board, for this reason the weight factors imposed to define the boundary conditions awarded the readiness of the considered systems. Hydrogen storage also, suffer heavily of the lack of a proper hydrogen distribution infrastructure. For this reason other energy vectors have been considered and a comparison model considering LNG and hydrogen storage systems was built and used to assess the most feasible solutions. Figure 79 shows the results of the analysis.

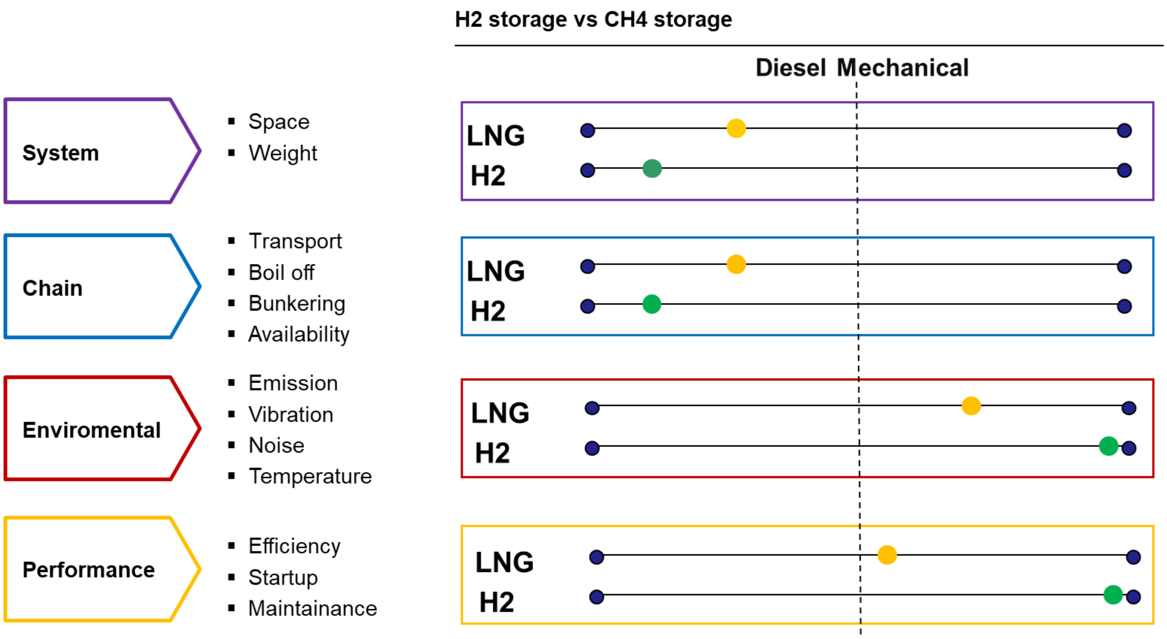


Figure 79. MY75 Project energy storage system comparison model results

As resulted from the assessment, a clear indication on the best energy storage system was not found. At this point it has been chosen to increase the importance of a zero emission operative profile. Only pure hydrogen is able to fulfil the requirement because LNG brings methane slip and CO2 production. Among the available hydrogen storage technologies two have been considered valuable for this project: Compressed Hydrogen storage (CH2) and Metal Hydride hydrogen storage (MH2). Liquid hydrogen has been dismissed because of the difficult bunkering operation and limited technology maturity. The final choice on MH2 depended on a series of factors:

- The possibility to store Hydrogen at low pressure (<10 (bar)). At the time IGF code was not available and the IMO interim guideline MSC 285(86) was specifically defined for the use of LNG and ICE. For this reason the limitation imposed by IGC code was used. Among them, "Gas in a liquid state may be stored in enclosed spaces, with a maximum acceptable working pressure of 10 (bar)". Afterwards the DNV Classification Societies state that during MH charging phase the MH internal pressure could rise. For this reason MH tanks were installed outside the resistant hull.
- MH don't require high pressure to be refilled. For this reason they could be virtually directly refilled by an electrolyser without the necessity to have a hydrogen compressor. The possibility to install a hydrogen generator on-board was assessed and considered as a feasible solution to overcome the lack of hydrogen availability.

Figure 80 shows the results of the Fuel Cell Room design. Two FCS power plant have been considered in order to respond to the Hotel requirements only or to power a small speed propulsion. For this reason the FCS was designed with two modules of 250 (kW) and various configuration with 250 and 500 (kW) FCS maximum power have been designed. In both the cases the BoP comprising cooling system, control, air system has been sized.

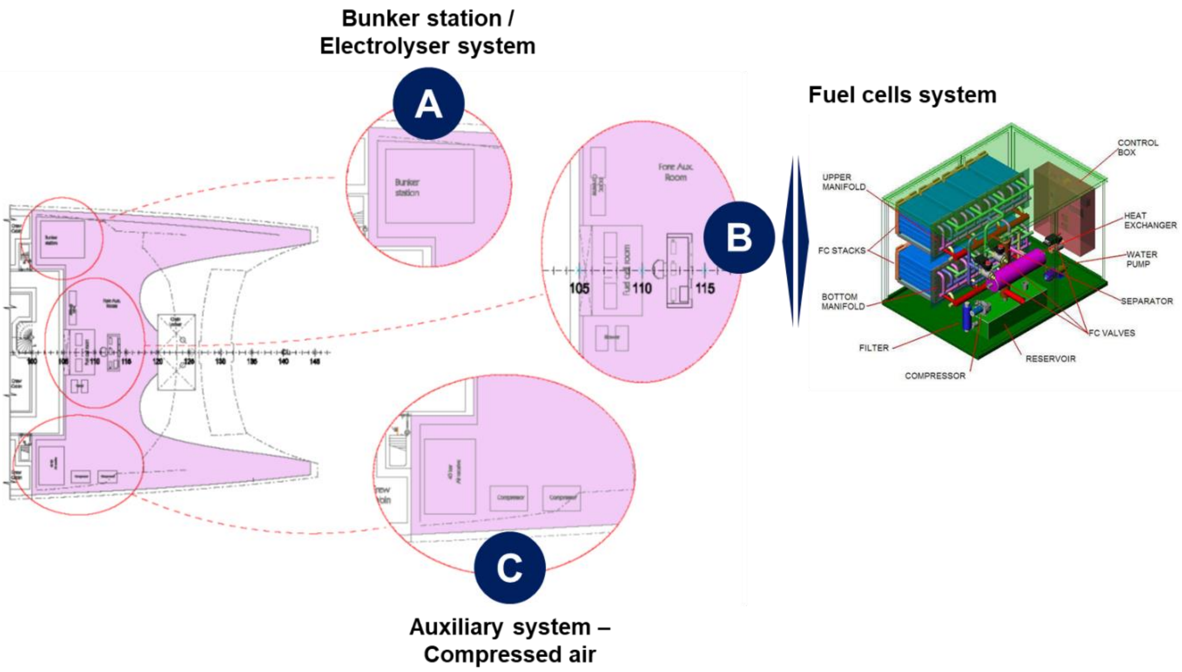


Figure 80. MY75 Project FCS Room design

The FC Room was designed in accordance with the DNV rules due to the lack of international guidelines. This aspect resulted to be the largest obstacle to the acceptance and introduction of the concept in the market.

The hydrogen storage system was designed considering MH storage tanks with external heat exchange.

This solution has been designed similarly to the one already present on-board the submarines built by Fincantieri for the Italian Navy. The choice comes also from the decision to install the MH tanks outside the resistant hull. Figure 81 shows other binding rules that have been followed for the installation of the MH storage system. The former where derived from IGC code and the MSC 285(86) guideline. The system was designed to store 2500 kg of hydrogen, able to power the yacht at 6 (kts) for 500 (mn) or the auxiliary system for 10 (days).

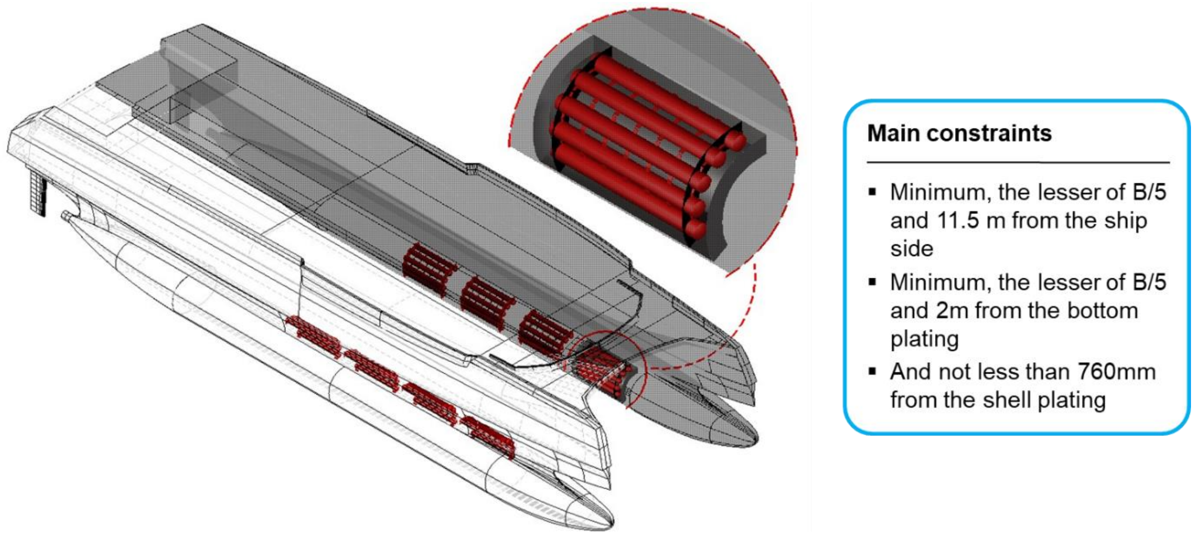


Figure 81. MY75 Project MH2 system design and rule constriction

In conclusion, the MY75 Project represented the first application of the studies conducted on the application of hydrogen technologies on-board ships. The concept didn't succeed to find a customer, mainly because of the lack of proper international rules. The project gave also other important lesson on the definition and use of comparative models, the construction of fuel cell power systems, the definition of fuel cell modules, fuel cell's BoP and MH storage system design.

Moreover, the project shows the difficulties related to the high power requirements (MW) and long range required.

4.2 PAX Project

During 2014 another Fincantieri initiative launch an important branch of study related to the marine application of hydrogen technologies. The initiative was the "Fincantieri Challenge", a call for innovation to rock the traditional ship design and introduce new products in the shipping market. The contest catalysed the energy of the Marine and Mechanical department of the University of Genova giving birth to an important mixture of competences and ideas. The result was the project presented in the box at the end of the chapter.

The "Fincantieri Challenge" target was a Passenger Ship. What has been developed during that contest was lately investigated and is at the present an important branch the study for the application of hydrogen technology in the maritime sector. The follow studies have been called "PAX Project" because the ship target is represented by the passenger ship "Diadema" of COSTA. The study has been divided into three parts: distributed energy generation, co-generation and tri-generation, on-board installation. It represent the clearer example of how the introduction of hydrogen technologies tends to bring alternative design approach and innovations within its application on-board ships.

Gross Tonnage (GT)	133019
Length over all [m]	306
Moulded breadth [m]	37,2
Passengers (max)	4947
Number of cabins	1862
Crew	1253
Cruise speed [knots]	20
Engines (type)	4x Wärtsilä 14V46C 2x Wärtsila 8L46C
Generators total output [kW]	67200
Propulsion (machinery type)	Diesel – electric

Table 53. Costa Diadema specifications

Table 53 shows the main characteristic of the ship. Two important observation can be made from these data: The total required power is very high; The installed power is fractioned into 6 generation sets. These aspects will be analysed at the end of the preliminary study.

. The study required input information from the ship builder (Fincantieri) and the ship owner (COSTA Crociere) and took advantage of the collaboration between the Department of Naval Architecture and Marine Technologies and the Mechanical Department of the University of Genova. Due to the confidentiality of the data elaborated in the study, only a broad presentation of the project is given. The PAX Project results brought to the launch of a more detailed study with the collaboration between Fincantieri and UNIGE.

4.2.1 Distributed Energy Generation (96)

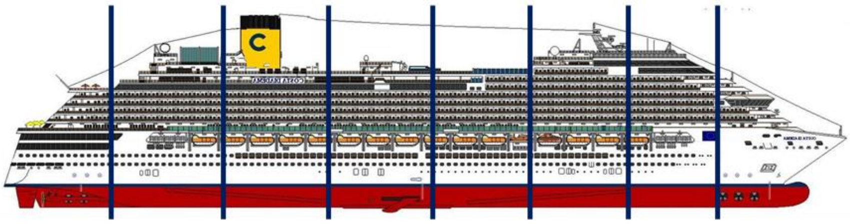


Figure 82. Scheme of MVZ subdivision of a Passenger Ship

The main goal of the study was to increase the ship flexibility in terms of power generation during normal and emergency situation, enhance the energy efficiency and reduce the emission generation. In order to comply with these requirements, it has been chosen to focus the study on the "distributed energy generation". In principle the ship can be considered as a medium size town, for this reason the same strategies have been applied. In terms of energy efficiency and flexibility the energy sector is developing the concept of "grid", later developed to "smart grid". The former consider the sections (district or houses) as energy consumer as well as power producers. The idea is to shift from a large central generation station to a distributed, fractioned grid of small generators. The concept has been already studied during the Pa-X-ell Project (97), decentralized energy grid based on fuel cell systems for hotel supply and conventional combustion engines for propulsion systems.

The study considered to divide the ship into 8 zone coincident with the already existing MVZ. From the on-board application sub-study, the power size of 1.125 (MW) has been found as target for the distributed generation units.

Following the experience maturated during the MY75 Project, a comparison model that considered different fuels and generators was designed. In particular Hydrogen and LNG have been considered as fuels and ICE, TG and Fuel Cells as generators. Table 54 report the final results of the analysis.

	ICE	Micro-GT	PEM-FC
efficiency	1	0	2
Fuel treat. Sys.	1	2	0
Air supply system	1	0	2
EGTS	1	2	2
Exhaust aux	0	2	2
Vibration	0	1	2
Weights	2	1	1
Engine room mod.	0	1	2
Space required	2	1	0
Maintenance	1	1	1
Electric aux	2	0	0
total	**11**	**11**	**14**

Table 54. Pax project generators comparative model results

A fuel cell power system has been designed, focusing on the weigh and volume of the fuel cells and their BoP systems. The goal was to define a stand alone power generation unit able to be installed easily inside the ship Figure 83 shows a three dimensional example of a fuel cell module and a battery module first and of a fuel cell power system space.

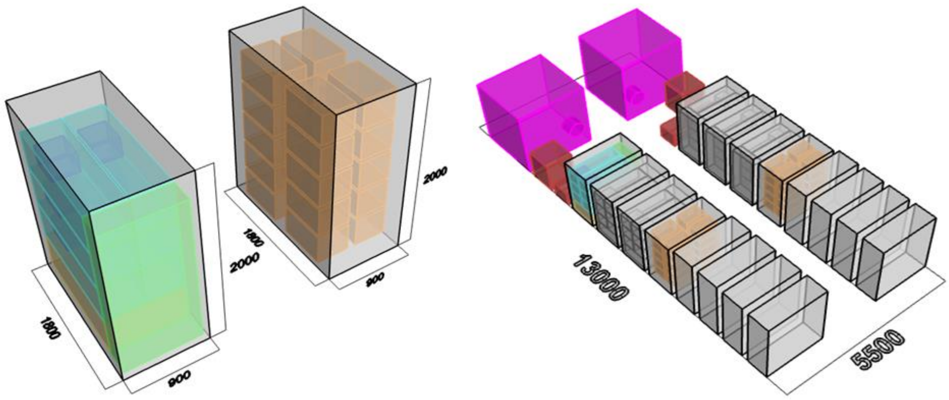


Figure 83. FCS rack and FCS room design example

Another result of the preliminary study has been the choice to use LNG as energy vector. The choice derive mainly from external consideration regarding the fuel availability. As the on-board application section will show, the required dimension of the natural gas reformer are not compatible with the available space on-board. Moreover an analysis of the saved CO2 of different power generator configuration has been done showing the reduced impact that a LNG+Reformer solution would have. These two factors bring to important observations on the benefit of using different energy vectors from hydrogen when a PEMFC power system is considered. Table 55 shows the emission comparison.

	Diesel engine	Fuel cell system H_2	Fuel cell + reformer
Total fuel consumption [kg]	17197.08 diesel	4998.67 H_2	17595.99 CH_4
Mean efficiency	0.3979	0.4875	0.3349
CO_2 emission [kg]	54114.05	0	56526.05
Saved CO_2 emission [kg] ~ [%]	-	100 %	- 2412 ~ - 4.45 %
NO_x emission [g/kWh]	*8.6147 ~ tier II*	0	-

Table 55. Potential NOx and CO2 emission reduction

4.2.2 Co-generation and Tri-generation (98)

Another important aspect of the distributed generation is the favourable possibility to use the excess heat produced by the electric generators taking advantage of the vicinity of the former to the final user (berths). Co-generation require the compatibility of heat and temperature. The analysis has been conducted for the three considered technologies that have been examined: Gas Turbine (TG), Internal Combustion Engine (ICE) and Fuel Cells (FC). Figure 84 shows the comparison of the required heat against the heat produced by the different generators.

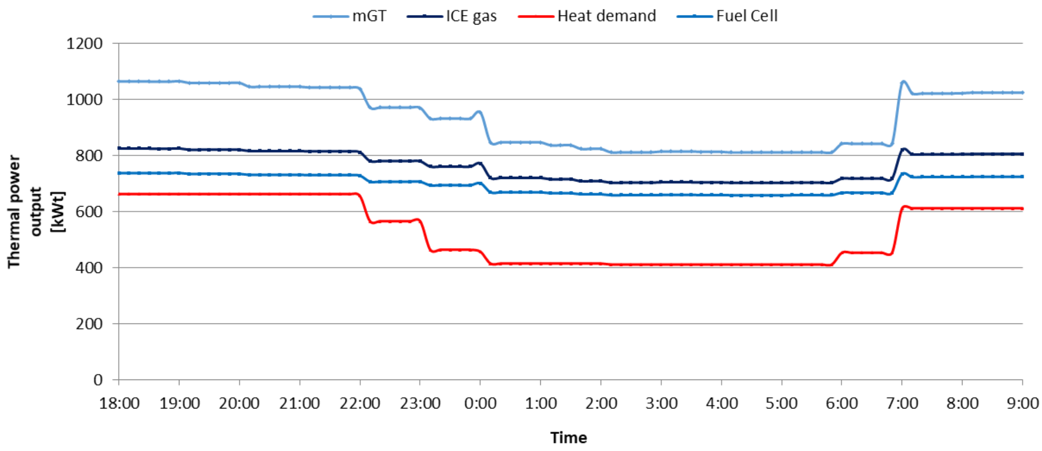


Figure 84. Heat production from generators, comparison

In order to analyse the compatibility of electric and heat request profile with the electricity and heat produced by the generators. In order to perform the study, the Web Economic Cogenerative Modular Program (W-ECoMP) software was used. W-ECoMP is a software environment aimed at the thermo economic time-dependent analysis and optimization of conventional and innovative energy systems throughout the year, in off-design conditions. Using this software it is possible to create a model representative of the energy system and run it, simulating the different operative conditions and evaluating both economic and thermo-energetic aspects. In this case the economic evaluation has been left aside to focus on the thermo-energetic aspects. Figure 85 show an example of the software visual interface.

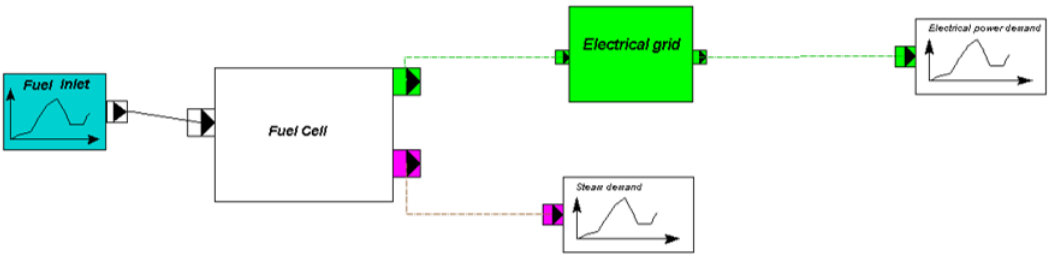


Figure 85. W-ECoMP visual interface example

Along with the co-generation analysis, the three-generation systems have been analysed in terms of performance, weight and volumes. The overall results are very poor, for this reason the three-generation has been considered not compatible with the available on-board space. Only revolutionary design that take into account the presence of distributed generation of electricity, heat and cool fluids can possibly be feasible. A new ship design though would require a much deeper study.

From the analysis of the steam flow and thermal balance of the ship it has been found that the distributed energy generators are able to produce enough heat to supply the hotel request but insufficient to the production of fresh water.

4.2.3 On-board application (99)

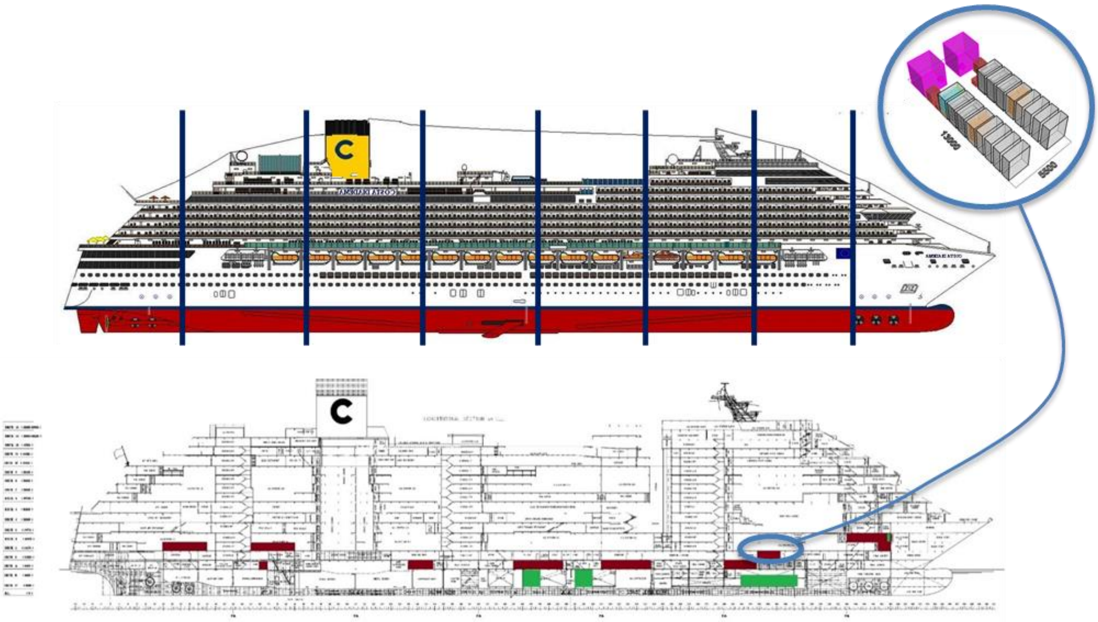


Figure 86. FCS arrangement scheme

The final part of the study consisted into the analysis of the ship characteristics (Electric and Thermal balances and profiles), in order to define the power size of the generator units. Moreover an analysis of the available spaces for the installation of the distributed generation system on-board the ship has been conducted.

BE Diadema	Nav. Max [kW]	Manoeuvring [kW]	Summer in harbour [kW]	Navigat 10 kn [kW]	Navigat 20 kn [kW]	Winter in harbour [kW]	Nav. All gen [kW]
A – Hull and deck service	63,7	8010,6	50,8	111,6	111,6	50,8	111,6
B – Safety service	131,2	153,5	126,5	131,2	131,2	126,5	129,3
C – Propulsion service	44360,8	2530,8	500,4	12841,4	25521,4	500,4	38081
D – Engine service	5274,4	5087,9	4248,5	5076,1	5251,1	3579,6	5257,6
E – Air con Service	5984,4	5985,1	5985,1	5985,1	5985,1	2912	5947,8
F – Galley Service	1218,4	1218,5	1219,3	1219,3	1219,3	1218,4	1218,4
G – Accommodation service	1023,4	1158,9	1165,3	1023,4	1023,4	1159,8	1020,4
H – Lighting service	1551	1701,5	1701,5	1551	1551	1701,5	1551
Total power required	**59607**	**25847**	**14998**	**27939**	**40794**	**11249**	**53317**

Table 56. Costa Diadema Electric Balance

Considering the high power required to propel the ship, an auxiliary system dedicated to the production of energy for hotel load has been designed. The goal was to equip the ship with a zero emission operative profile able to supply energy to the ship when she's still in the harbour. A comparison data analysis between the Electric Balance (Table 56) supplied by the ship builder and the real power consumption data of a similar ship supplied by COSTA show that real consumption values are about 21% lower than the ones of the Electric Balance. Considering this difference together with further hypothesis on the power reduction of Propulsion services and Engine services, an average value of 9 (MW) has been considered sufficient. From the power analysis and the exploitation of the MVZ as generator district, the value of 1.125 (MW) has been found as average power size for the distributed generators. In some case MVZ with higher power have been designed compensated by MVZ with limited power request that have been equipped with smaller generator units.

The study considered as biding the original ship design, meaning that only secondary structures have been moved to make room to the system, without considering structure analysis. The process has been developed taking into account the same rule framework that was considered during the MY75 Project. Today the IGF code has been amended with many additional parts while the code section dedicated to the installation of fuel cell is under development.

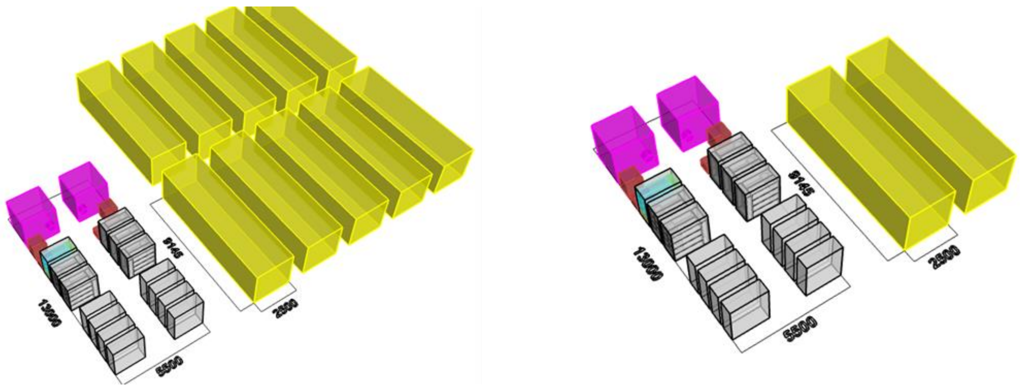


Figure 87. Methane SR dimensions vs Diesel ATR dimensions

An important result of the preliminary analysis has been the feasibility study on the installation of the reformer units required to supply hydrogen to the fuel cell power units. The arrangement exercise has been conducted even if from Figure 87 was already evident the difficulty to find enough space to the system. The comparison show that a diesel reformer on the contrary would represent a much more feasible solution. In any case the CO2 production analysis shows that the advantage of the use of reformers to avoid hydrogen storage systems is limited.

Figure 88 shows an example of the arrangement analysis that have been conducted using the ship general plan. The former rise important observation that are resumed in the preliminary study results.

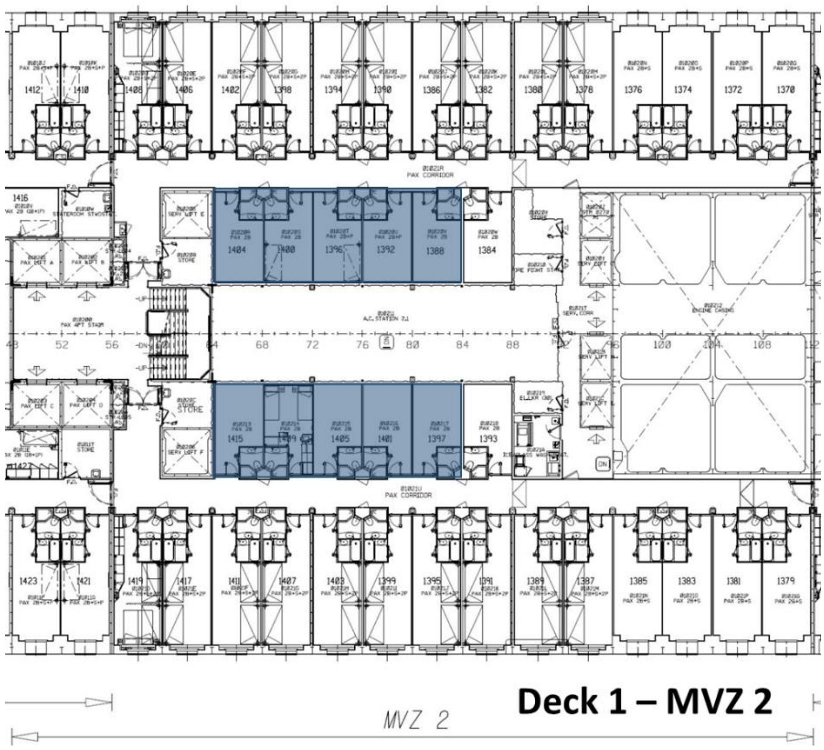


Figure 88. FCS arrangement example

4.2.4 Conclusion

Important observation can be made on the preliminary analysis for the application of hydrogen technology on-board a passenger ship:

- Almost all modern passenger ships are diesel-electric, meaning that the propulsion is provided by electric engines powered by the on-board electric grid. The former is powered by diesel generators of the MW size in order to comply with the Electric Balance that require about 10 (MW) for the hotel service and about 50 (MW) to the propulsion. Hydrogen technology due to the poor performance of hydrogen storage systems are not able to supply the whole required power. In order to be effective FCS have to respond to specific problems: emission restrictions, environmental challenge, comfort, and image. These requirements bought to the definition of dedicated "fuel cell operative profile" that can be used by the ship to comply with emission restriction in special area, reduce the environment ship impact, increase the comfort locally and provide a "green" image to the ship owner. The maximum power size of a fuel cell power unit has than been found in about 1 (MW) to power auxiliary systems mainly, and only limited propulsion (6 (kts));
- In order to be more effective, lower power demand Electric Balances should be aimed as targets. The former can be found in smaller passenger ships that on the contrary provide less space to arrange the systems on-board. It's a belief of the author that the most feasible ship platform for the introduction of hydrogen technology is represented by High Luxury Passenger Vessels, that present lower power requirements, higher presence in special ECA zones and are frequented by persons with higher environmental sensibility;
- The preliminary analysis assess also the possibility to use the Distributed Energy Generators to power a Safe Return to Port operational profile. The SRtP though have very tight requirements on the ship propulsion such has it is thought to be out of the Distributed Energy Generators possibility;
- In order to enhance the efficiency of the FCS and distributed generation, co-generation should be taken into account;
- The hydrogen technology application on-board a passenger ship comply particularly well with the distributed generation requirements such as that a future FCS application is believed to have this system architecture;
- Hydrogen storage result to be advantageous against LNG or Diesel reformer for this the above-mentioned application. Another promising solution, that has not been investigated at the moment, is the use of Methanol inside HTPEMFC equipped with MeOH reformer, as demonstrated by the Pa-X-ell project.

4.3 Sailboat applications – the H2Boat Project

It has been proved that hydrogen technology is able to fulfil maritime requirements in terms of power generation and energy storage. But its application on-board ships still remain difficult due to the extreme high power installed and to the volume and weight of the hydrogen storage systems. As a matter of fact, what is considered the future technology for ships, LNG, is facing the same challenges trying to respond to the emissions limitation imposed by the IMO, that with the promulgation of annex VI of MARPOL is guiding the shipping transport towards environmental friendly standards.

For these reasons it has been chosen to pursue the development of the system on smaller vehicles, to set upon niche markets with focused innovative solutions. The chosen target is the sailboat, that present many advantages:

- lower installed power,
- particular disposition of weights,
- ship owners special inclination toward greener systems,
- large utilization of renewable power generation (PV panels, wind generators)
- relative high price of boats.

The idea, is to develop a modular system (Energy Pack) able to be scaled up in terms of power and stored energy in order to be adapted to other larger boats first and ships later, once technology improvement, infrastructure diffusion and rule framework will be mature enough. Hydrogen technology provide an ideal route towards the system development thanks to its scalability.

The energy pack is designed to work inside a hybrid system, increasing its functionality, but to design a feasible system, the assessment of the boat/ship operational profile to be met is required. Balancing between the advantages (mainly the on site total reduction of pollutant emissions and the extremely low noise) and the disadvantage (or rather costs, on board weight/volume and fuel availability) of this technology, the following scenario has been developed:

Auxiliary power production for special harbour operational condition and for stay in restricted pollution areas, including low speed approaching for on site sailing operations.

This operational profile is required for many boats and ships, but the new IMO rules will require to all maritime transport systems to reduce or eliminate any pollutant emission in the future, enhancing the market application of the system.

The Energy Pack has been designed to be installed on-board boats and ships, choosing the most compliant solution for the maritime sector (PEM, Metal Hydride, Electrolyser). The solution is able to work in stand alone applications as well as inside a complete infrastructure to solve local problems (local emissions, noise etc.) at first, aiming to change the ship into a centre of storage and consumption of renewable energy, with zero CO2 emissions.

The final product target will be a pleasure sailboat of 12-15 (m) long, but to prove the performance of the system, a race sailboat has been designed as prototype. The concept idea then is a complete engineered prototype that comes from the basic design of the EGO 650, a Mini Class sailboat designed by Skyronlab design.

4.3.1 The Concept

The concept comes from the adaptation of a Energy Pack to a sailboat. In the following a complete description of both, the boat and the energy system design will be given. The following concept study began from a Start-Up competition that give birth to H2Boat S.c.a.r.l., a UNIGE Spin-off.

4.3.2 State of the Art

A general sailboat can be characterized by:

- dimensions (length between 10-18 m);
- main engine connected to a single propeller and a shaft alternator (power range of 20-100 kW);
- a DC on-board electrical system (12 or 24 V);

- a service battery pack (between 150-250 Ah, 12 or 24 V).

Moreover the ship owner tends to limit the usage of the main engine to sail and to exploit the electrical storage when the ship is still at the anchor or whenever electrical power is required. The usage of the engine to power the electrical system is reduce to the minimum, to power the propeller and to recharge the batteries. In fact, during the last years PV panels and wind generator applications on-board sailboats found a large diffusion in order to reduce the battery energy storage consumption. A general scheme of the power system installed on-board a sailboat is presented in Figure 89.

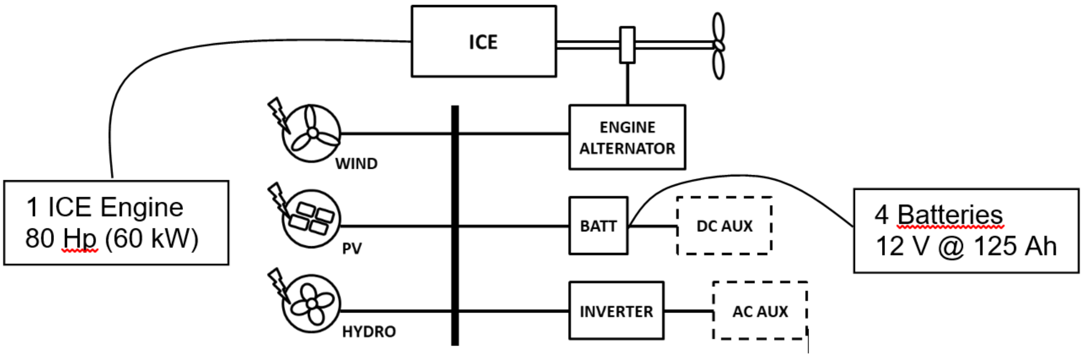


Figure 89. General sailboat Power System

The previous scheme represent a traditional system, that is characterized by the direct connection between the engine and the propeller (a gearbox can be present). Inside this configuration usually the following technology are used:

- ICE-Diesel engine;
- BATT- Lead/acid deep cycle batteries.

From literature it can be found that this configuration is used whenever the difference between the required Power&Energy of the propulsion system and the required Power&Energy of the Auxiliary system is large. When this difference is reduced at the point that the figures are of the same magnitude order, a hybrid configuration is favourable. Indeed this justification result to be valid only for large ships like passenger ships or special military vessels.

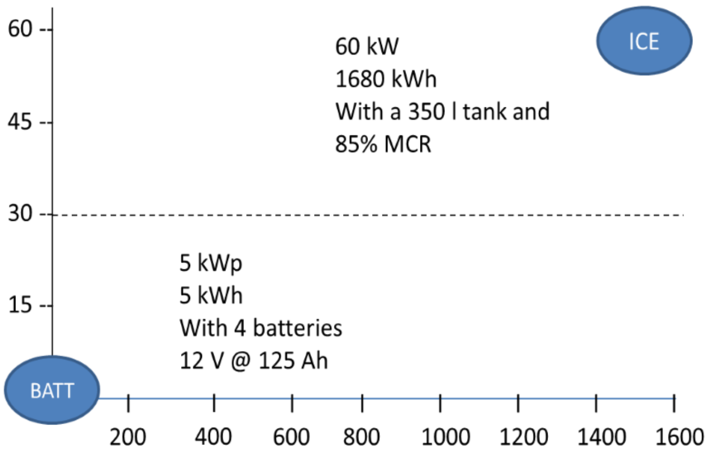


Figure 90. Typical figures for a 15m sailboat - Main Engine vs Service Batteries

For what concern other vehicles like sailboats, the reason that lead to the adoption of a hybrid system are to be searched in other motivations like reduced consumption, increased comfort, increased automation, special operational profile (low emission profile).

This framework brings to an increasing demand of energy (auxiliary systems for comfort, automation) with limited power. Comfort for example means the availability of AC current to power computers, televisions or other electrical equipment while automation is represented by bow thrusters or electric winch, all electric system with limited power request. As results the configuration has been changed as explained in the following Figure 91.

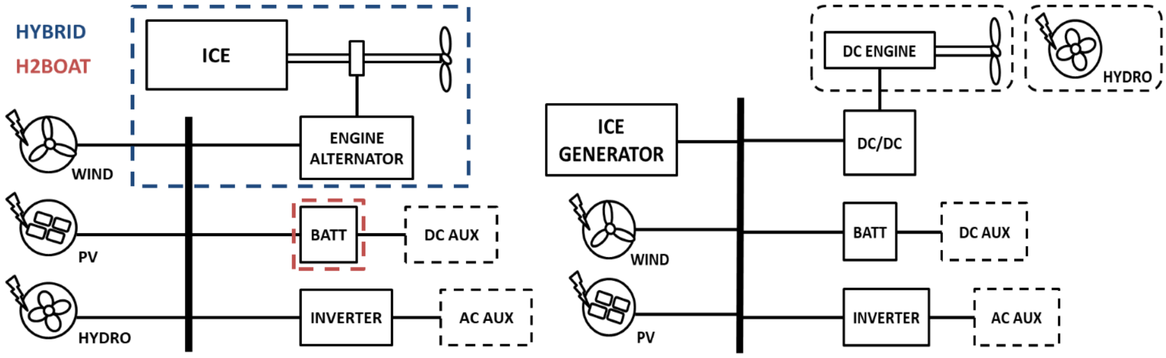


Figure 91. New Hybrid Power System configuration

4.3.3 H2Boat

Starting from the new hybrid configuration, the H2Boat innovative solution tries to improve the performance of the battery (BATT) component while the ICE, should be replaced by a ICE Generator. There are many electric generators available on the market for marine applications, that generally are used to power the electrical system instead of the main engine, because of the higher efficiency. The same solution can be used in a hybrid configuration to give power to the propulsion system when required. The increased efficiency of the generator will obviate to the power loss due to the efficiency chain of the hybrid system (mechanical to electrical to mechanical power), but it could increase the required volume of the propulsion system, depending on the electric engine that is considered.

For these reason, it results important to increase the performance of the BATT component without increase volumes and weight. The H2Boat solution consists in the adoption of a ***Energy pack*** composed of three components together with an ***Innovative Design*** of the boat keel.

The ***Energy Pack*** is composed by:

- A PEM fuel Cell, fuelled with hydrogen, to produce electrical power at zero emission
- A MH hydrogen storage system, to store large amount of energy in the form of hydrogen
- An Electrolyser, to produce hydrogen from electrical energy

In Figure 91 a general scheme of the system is presented while Figure 92 presents a more detailed scheme of the components integration, that shows the complex management of electricity (black), hydrogen (red), heat (orange) and water (blue) flux. The idea is to exploit the integration of the components over all the controlled fluxes, so that the heat produced from the FC is given to the MH to help it to release the hydrogen that fuels the same FC. Or the water produced by the FC that is stored and used by the Electrolyser to produce hydrogen when a surplus of Electrical Power is produced by the Renewables. All the considered components are available on the market, the real challenge is represented by the system sizing and control. In order to comply with this problem a Simulation Tool has been designed. At the present the Tool is under validation in the Laboratory of the Thermochemical Power Group of the University of Genova.

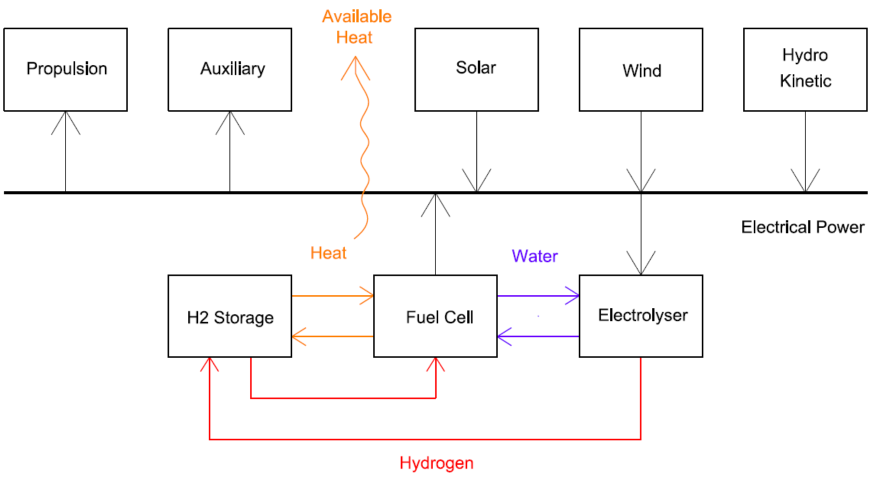


Figure 92. Energy Pack scheme

An ***Innovative Design*** of the hull is required to exploit the potential of the Energy Pack. Figure 93 shows how the plan of a general sailboat has been analyzed and improved.

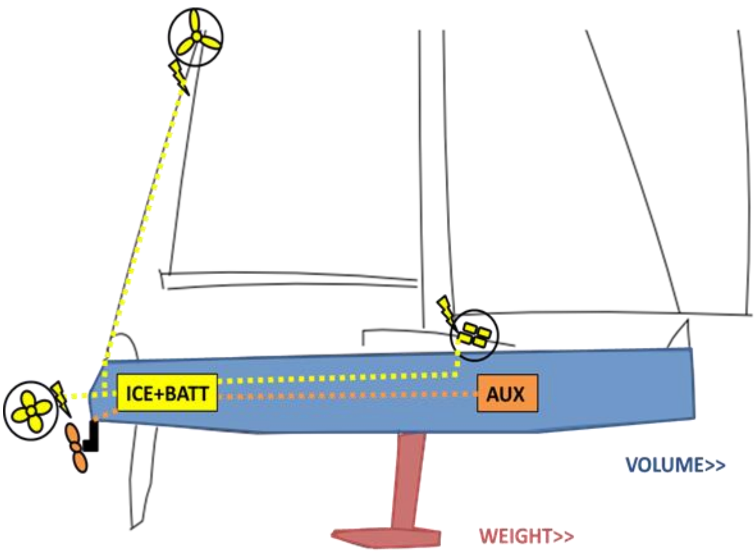


Figure 93. Sailboat general plan

The figure highlight two main factors concerning the boat plan:

- Electrical energy center of production (yellow) and consumption (orange);
- Space characterized by high importance of payload volumes (blue) and the space characterized by high importance of specific weight (red).

The first point has been explained previously, and the present available solution to optimize the energy balance onboard is represented by the hybrid system. The second point is part of shipbuilders and engineers knowledge. In particular, the position of weights is fundamental for the stability of the boat, this is one of the reason why, heavy batteries cannot be accumulate on the deck reducing precious volumes and compromising stability.

The sailboat analysis has been conducted taking into account the previous considerations and the following factors:

- Potential exploitation of renewables onboard;

- Characteristic of the Energy Pack (weight, volume, power, energy).

It has been proven (60) that renewables onboard are able to produce a potential average energy of 2.6 (kWh/day) on a small sailboat equipped with 200 (Wp) PV solar panel, 300 (Wp) wind energy generator. Depending on the operational condition the energy production can increase to 4.5 (kWh/day) with the boat still at anchor while much more energy can be produces if a 500 (Wp) hydro generator (common equipment available on the market) is considered when the boat is sailing. This large amount of potential energy can only increase with the increasing performance and integration of onboard renewable power production systems. The limiting factor though, is not cost but energy storage. Indeed, batteries energy density is low, even if lithium batteries are considered. Moreover, increasing the battery energy storage require to install more batteries on the deck.

The Energy Pack can be considered as an electrical energy storage like a battery but with important differences. The main difference is the separation between the components assigned to the production of electrical energy (PEMFC) to the one assigned to the storage of energy (MH2). This characteristic allow to increase independently the storage capacity or the power generation. Moreover electrolyzer hydrogen production is less influenced by voltage oscillation from renewables than batteries are during charge phases. As results from the analysis, it has been chosen to design an innovative keel able to store the MH tanks (characterized by elevate weight) exploiting a volume that usually is not considered. Furthermore thanks to the electrolyzer and the large availability of energy storage, the renewables potential can be finally exploited. A more detailed explanation is given afterwards, in the following a scheme of the functioning of the system is presented.

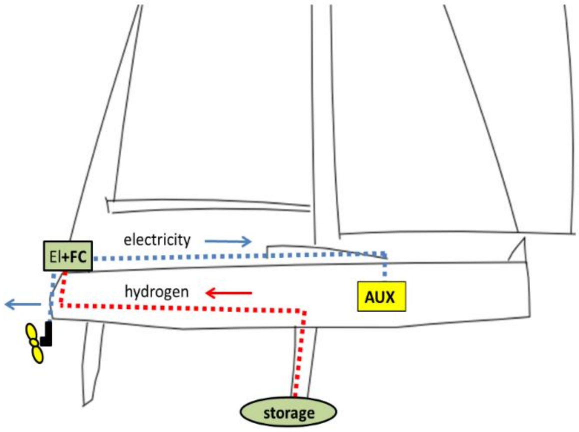


Figure 94. Power production configuration

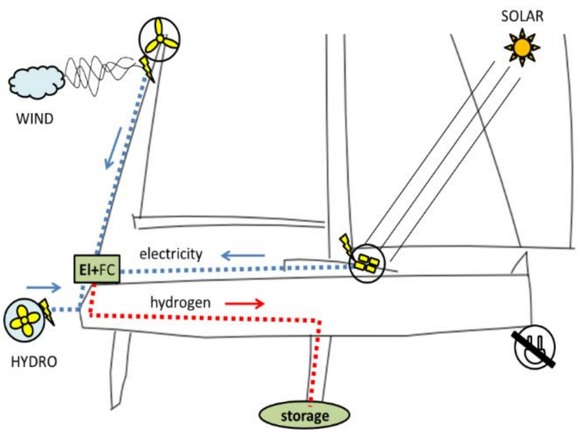


Figure 95. Energy production configuration

When electric energy is required and the renewable are not able to supply it, the Energy Pack extract hydrogen from the MH storage to fuel the PEMFC, Figure 94. If the system is properly designed a reduced propulsion profile can be considered. When a surplus of power energy is produced by renewables the excess power is used to produce hydrogen to refill the MH tank, Figure 95. If needed, the energy storage can be refilled when the boat is at berth using shore electric supply.

4.3.4 Sailboat design

The hull that has been chosen to install the first prototype of H2Boat is the Mini EGO 650, designed by Skyronlab. This sailboat has been chosen because it's one of the most challenging sailboat class for solitary race, and thanks to its small dimension the production cost is limited. Furthermore the Mini Class association organize every two years the famous Mini Transat also known as Transat 650, one of the most famous solo transatlantic yacht race. For these reason the mini sailboat and the race are admitted to be a "test bench" for systems and mechanisms to be used on bigger and far more expensive open classes.

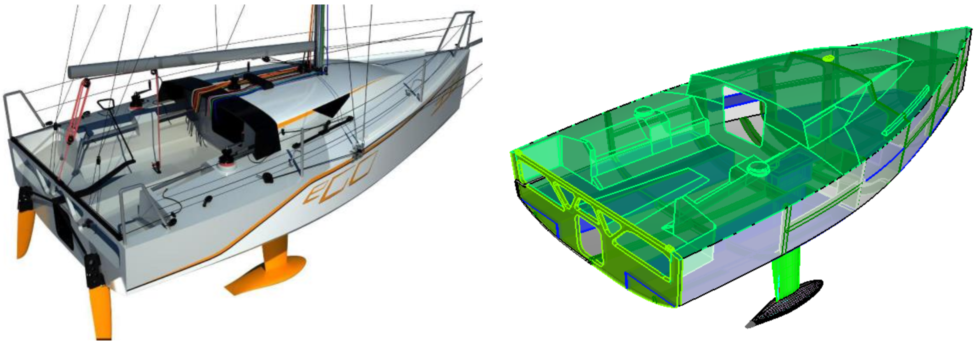


Figure 96. The Mini EGO 650 of Skyronlab.

The main technical specification of the boat are reported in Table 57.

Length	6.50	m
Beam	3.00	m
Mainsail	25	m2
Genoa	19	m2
Ginnaker	75	m2
Draft	1.6	m
Displacement	950	kg
Keel Bulb	430	kg
Material	fiberglass	-

Table 57. EGO 650 main dimensions

Figure 96 shows the structure that has been considered for the installation of the Energy Pack. The boat's rudder, the mast and the steer systems in general has not been considered, while the integration design focused on the keel.

4.3.5 Electrical Balance – SOA

An assessment of the electrical equipment and of the electrical production/storage systems has been done. Six main groups of electrical equipment can be identified: Autopilot, Navigation systems, Positioning systems, Communication systems, Audio and Video systems, Other. Among the various voices the one that require the higher power is the Autopilot with 300 (Wp). The on-board electrical system is 12 (V) direct current and is powered by lead/acid batteries, a mandatory equipment. Since the stored energy inside the batteries is not enough, different systems are used to recharge them. Today, three main method are used:

- Small ICE generator;
- Renewables (PV panels and wind generator);
- Fuel Cells.

Renewables are gaining more and more importance but because of the random presence of the sources they cannot be considered a complete solution. ICEs are the most typical solutions, that are affected by the presence of gasoline, the production of exhaust gases and noise. Fuel cells are already in use, but the used systems are fuelled with Methanol. These systems are equipped with a reformer that produces hydrogen from the methanol to fuel a PEMFC, are characterized by lower efficiency and reduced reliability since the reformer is sensitive to the boat inclination.

An assessment of the used technology can be found in (100), in the following three common example are given.

- Batteries. Fiamm LSB 100;
- ICE Generators. Honda EU 10i;
- Methanol Fuel Cells. Efoy comfort 210.

Fuel cell systems allow to provide a continuous charge to the batteries in an automatic way engaging the skipper only in the fuel tank replacement stage. Furthermore, given the low power output of the Methanol FC systems, it is necessary to embark at least two fuel cells to have adequate power. The ICE Generator needs to run cyclically for fast charging cycles of the batteries that require the skipper attention. Batteries are mandatory. Table 58 shows the technical data of the described systems.

EU 10i		
Power	1	kVA
Voltage	12	V
Dimensions	450x240x380	mm
Weight	13/15	kg
Volume	41	l
Consumption	0,3/0,6	l/h
Autonomy	4.4	h

EFOY COMFORT 210		
Power	105	W
Voltage	12	V
Dimensions	443x202x288	mm
Weight	8.5	kg
Volume	26	l
Consumption	0.9	l/h
Autonomy	11.1	h

FIAMM LSB 100		
Power	>1000	W
Voltage	12	V
Dimensions	330x220x172	mm
Weight	32.8	kg
Volume	12.5	l
Consumption	100	Ah
Autonomy	4-1,2	h

Table 58. SOA Electrical Power Production

Finally, a detailed rule compliance analysis has been conducted (100), to prove the feasibility application of the new Energy Pack.

4.3.6 Energy Pack sizing

The design of the Energy Pack has been conducted through the simulation tool as better explained in the following chapter. The sizing of the system though has been done through the analysis of required electrical power (SOA analysis gives also the electrical balance) and the required energy storage. The last figure has been evaluated on the base of the average maximum energy required by a Mini sailboat to cross the longest stage during the Mini Transat, that is the Atlantic cross.

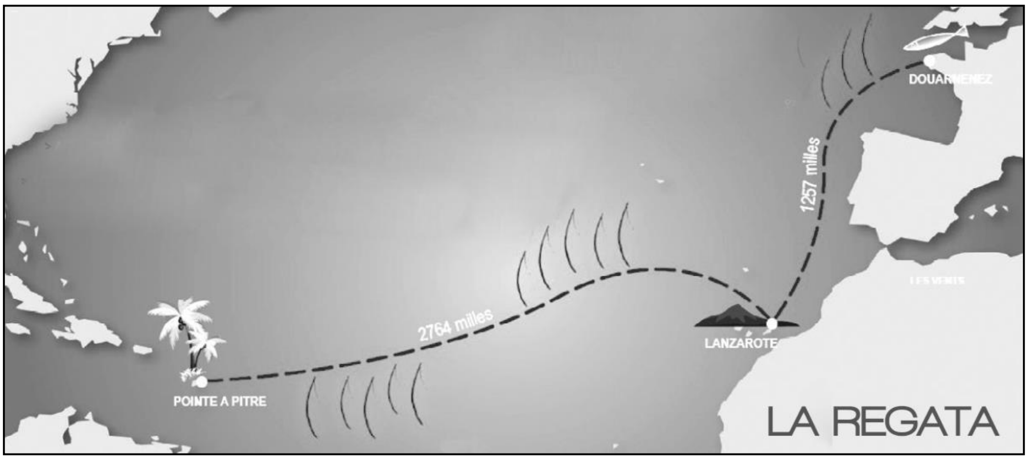


Figure 97. Mini Transat 2013 route

The study found that the longest stage, from Lanzarote to Pointe a Pitre (2764 nm) requires an average of about 20 days for a standard boat to be completed, 17 days for a prototype boat.

Duration			
Proto	min	16	days
	max	18	days
Standard	min	19	days
	max	22	days

Table 59. Total Mini Transat second stage time

The average daily energy requirement for the boat has been rated by the Italian skipper Federico Cuciuc in 0.5 (kWh/day), based on the 2013 edition data. This value considers only the energy required by the system to recharge the batteries but not the energy produced by photovoltaic. According to the skipper, with an allocation of new solar panels and an optimized energy management, the value of the daily energy requirements can be reduced to (0.35 kWh/day).

Energy Requirements A			
E	0,5	kWh/day	
Proto	min	8	kWhe
	max	9	kWhe
Standard	min	9,5	kWhe
	max	11	kWhe

Energy Requirements B			
E	0,35	kWh/day	
Proto	min	5,6	kWhe
	max	6,3	kWhe
Standard	min	6,65	kWhe
	max	7,7	kWhe

Table 60. Energy requirements

Fuel Cell

Fuel Cell means the complete system including the Balance of Plant (BOP). The chosen system for the project is the G300 HFC PEMFC system provided by Genport. Such a system corresponds exactly to the specifications identified for the project both in terms of power and of operating conditions. The G300 HFC was in fact designed to operate in extreme conditions in hostile operating environments (war scenarios). Therefore, it is able to operate at very accentuated degrees of inclination, strong vibrations, and in general lends itself to function under the conditions of use described by the skipper Federico Cuciuc.

Fuel Cell G300 HFC	Nl/min	kg/h	kg/kWh	m^3/kWh	Fuel Cell G300 HFC		
Max consumption	6	0,0295	-	-	Weight	19	kg
Consumption 300 W	4,5	0,0221	0,0738	0,9000	Volume	52	l

Table 61. Genport G300 HFC PEMFC specifications

The G300 HFC system features are shown in Table 61. The system looks like a compact case with the inputs for the fuel (hydrogen gas) and the electrical outlets of the power output. Compared to methanol fuel cells the exhaust gases are less harmful because the cell does not produce carbon dioxide but releases only depleted air.

The PEM-type fuel cells operate at temperature of about 70 (°C), producing a thermal power approximately equal to the electric one (average yields of 50%). Thus the air output from the cell will have a higher temperature than ambient temperature but absolutely compatible with the use of the system even in closed environments.

In addition, the project will implement a system of water cooling for the cell. This solution is more efficient from the point of view of the heat exchange and will also allow to exploit the heat produced by the fuel cell for the metal hydrides system. A more detailed description of this function is given in the following chapter.

Metal Hydrides

Metal Hydrides are systems able to accumulate and store hydrogen at low pressure and low temperature. For Metal Hydride we mean the cylinder that contain the metal hydride powder and an internal heat exchanger that is powered by a stream of clean water at a controlled temperature (35-40 (°C) for hydrogen release, 15-20 (°C) for hydrogen accumulation), able to absorb and release hydrogen with flux rates of the order of 500 (Nl/h) and pressures between 2 and 15 (bar). While the fuel cell is supplied as a complete system, the hydrogen storage system based on the metal hydride technology needs to be dimensioned. A preliminary market assessment has shown that a number of producers are available. The same MH tanks analysed in the laboratory towards the MH test rig have been considered. Figure 98 present some pictures of the MH cylinders, named HBOND.

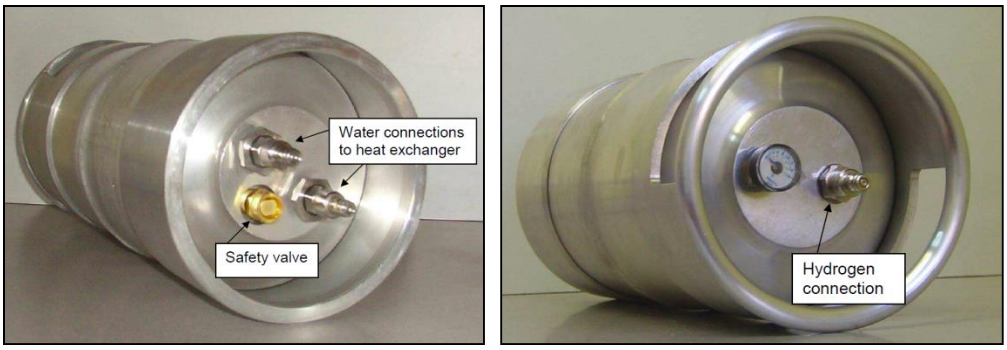


Figure 98. Labtech HBond MH cylinder (500 Nl)

Electrolyzer

The sizing of the electrolyser depends mainly by two factors: the maximum power available from the renewable sources and the time needed to refill the hydrides storage. These data have been considered in the evaluation of the complete system that has been made for a larger sailboat in (101). For this particular project the presence of the electrolyzer has not been considered.

4.3.7 MH storage system

The need to design the system from scratch has placed from the beginning an important technical choice:

- Design a single storage system able to exploit the maximum volumes of the keel;
- Design a keel able to accommodate commercial cylinders of metal hydrides for hydrogen storage.

Despite the relative simplicity of design and construction of metal hydrides cylinders, it was chosen to design a keel able to accommodate commercial cylinders. The reasons at the base of this choice are both technical and economical. The use of commercial cylinders allows to: reduce the risk of design errors, to take advantage of the best storage technology available, to construct a system that can be inspected, to divide the system into more cylinders, to reduce the cost of design and construction.

A preliminary analysis gives answer to the storage system (cylinders) optimum dimension, that are:

- Hydrogen required by the fuel cell?
- Thermal power required by metal hydrides?
- Space available?

The first question has been answered by the analysis of the G300 Fuel Cell and is reported in Table 62. A more detailed explanation of the sizing is available in (100).

The second point has been investigated through laboratory test and theoretical assessment. Starting from the MH Enthalpy of formation (30,8 (kJ/mol) H_2) the thermal power required to met the fuel cell hydrogen flow working at 300 (W) has been evaluated. The results is showed in Table 63.

Consumption 300 W	270	Sl/h	249	Nl/h
Max consumption	360	Sl/h	332	Nl/h
Stand by consumption	24-42	Sl/h	22-39	Nl/h
Max pressure	16	bara	15	barg
Min pressure	2	bara	1	barg
Hydrogen purity	>4.0	-	>99,99	%

Table 62. Fuel Cell supply specifications

Fuel Cell		
Pmax(electric)	300	W
Pmax(thermal)	450,0	W
Temperature	65	°C
Heat exchanger		
Thermal power	270	W
Metal Hydride		
Thermal power required	94,8	W
Thermal coupling		
heat flow available	+280%	-

Table 63. Thermal coupling

The third and last point required the integration of all the previous results to identify the better solution to the MH storage system integration inside the keel. The amount of energy that has been chosen to follow at the design level is 6.6 (kWh) (from Table 60).

4.3.7.1 Kell design

Starting from the dimension of different kind of HBond cylinders, the keel bulb design has been modified trying not to change the external dimension. The analysis has been done considering both form and specific weight of the final bulb in order to maintain the original stability of the boat. Since the MH specific weight is lower than the one of cast iron, a calculated amount of lead has been considered to balance the bulb. The following Figure shows the design process that has been followed.

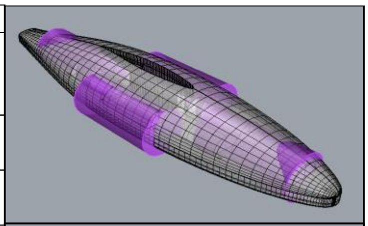
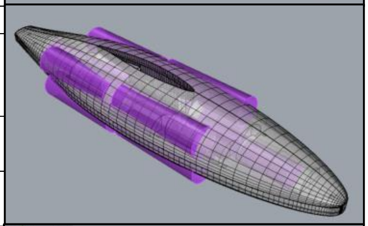
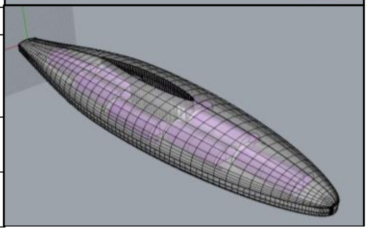
Hbond 1500					System 1		
d	145	mm	1.45	dm	4	#	
l	300	mm	3	dm	6000	Nl H2	
H2	1500	Nl	123	g	6.7	kWh	
W	14	kg	2.8	kg/l	keel bulb	4	
V	5.0	l			kg	56	
kg H2/m^3	24.8				deck	0	
wt%	0.88				kg	0	
Hbond 500					**System 2**		
d	80	mm	0.8	dm	12	#	
l	300	mm	3	dm	6000	Nl H2	
H2	500	Nl	41	g	6.7	kWh	
W	5	kg	3.3	kg/l	keel bulb	10	
V	1.5	l			kg	50	
kg H2/m^3	27.2				deck	2	
wt%	0.82				kg	10	
Hbond 300					**System 3**		
d	80	mm	0.8	dm	20	#	
l	180	mm	1.8	dm	5999.39	Nl H2	
H2	300	Nl	24.60	g	6.7	kWh	
W	3	kg	3.3	kg/l	keel bulb	8	
V	0.9	l			kg	24.0	
kg H2/m^3	27.2				deck	12	
wt%	0.82				kg	36.0	

Table 64. Keel bulb design

Part of the MH cylinders have been integrated inside the keel bulb and part of them have been installed on the deck, under the special request of the skipper (system 3 of Table 64). The reason comes from the possibility to have small concentrated mobile weights to be moved and placed in the stern of the boat to balance the boat inclination.

After the studies, it has been decided to patent the layout of the bulb structure and of the centreboard. The system has been designed in order to be scaled up easily and to create a safe transfer of gases from the bulb to the fuel cell. Figure 99 present a scheme of the keel bulb structure.

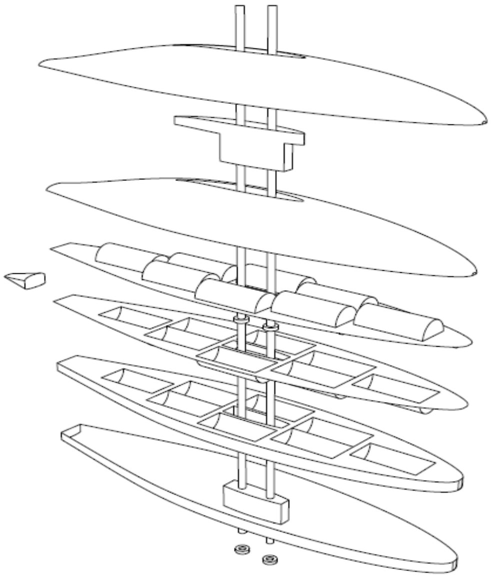


Figure 99. Keel bulb construction plan

The reason why the weight and the external form of the original bulb have not been modified is related to the fact that the project wanted to prove not only the feasibility of the installation of the system but also its performance. Indeed, without changing these dimension it has been possible to analyse the impact of the Energy Pack on the boat performance.

4.3.8 Keel performance

The boat performance has been verified through two different assessment. A CFD analysis of the fin keel and a stability analysis of the boat under different operational conditions.

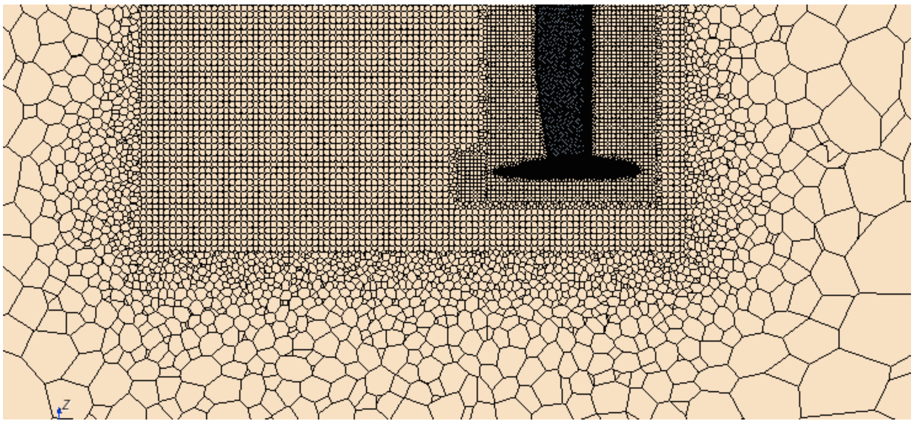


Figure 100. Example of Mesh construction for CFD analysis

The CFD analysis demonstrate that limited increase of the bulb volume involves very limited increase of hydrodynamic resistance (few percentage point). Indeed what increase the bulb resistance is the external surface enlargement, that produces limited penalization in the fluid dynamic performance of the bulb if the extra surface is generated in the cylindrical part of the form. In fact, what is more important for a good hydrodynamic performance is a well designed end of the form.

The stability analysis has been conducted against 6 different criteria for both the original sailboat design and the new one. Results demonstrate that the presence of the Energy Pack, integrated as explained in what has been called the H2Boat solution, does not influence in any way the stability of the boat as long as the weight value and their position does not significantly change.

4.3.9 Results

The last analysis that has been conducted has brought to the identification of the most convenient positioning of the Fuel Cells, the Electrolyzer and the deck MH storage systems. Figure 101 show the fuel cell/electrolyzer possible position (red) and the MH storage most feasible position (yellow). The stern positioning has been considered the best choice. This choice is also related to the presence of available volumes for many sailboat other than the Mini but also to the results of the rule compliance analysis (100) (101). Indeed the stern volumes are the ones that can be conveniently reached by and external pipe that pass outside the hull. A solution that can be used on-board existing vessels (refitting) and that comply against the most stringent rules.

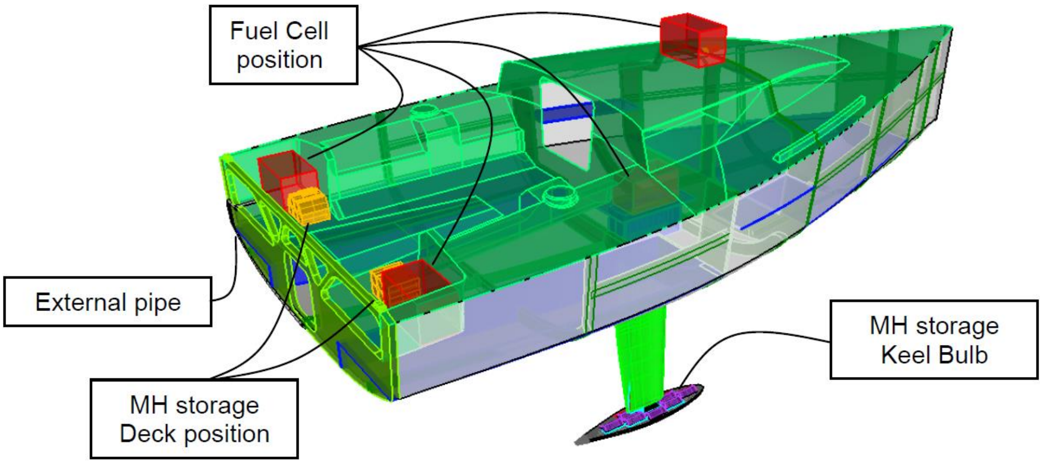


Figure 101. Energy Pack deck positioning

The H2Boat solution is able to give to the EGO 650, 6.6 (kWh) of energy without changing the original weigh of the boat, without reducing the available volume on the deck, without changing the keel bulb form. The presented solution is able to power the Auxiliary system of a Mini Class sailboat in a complete reliable, automatic, environmental friendly way.

It has been demonstrate that the prototype design can be improved changing only the keel bulb volume, doubling the energy storage capacity without substantial reduce the hydrodynamic performance of the keel.

It has been proved that the H2Boat solution can be easily scaled up for larger sailboat, motor yacht to even passenger ships. Indeed, during the study period, a concept study of Mega Yacht hydrogen power system has been done while the concept of the integration of fuel cells on-board a passenger ship is under study.

4.3.10 Future development

In the following an example of scale up of the H2Boat solution for a 15 (m) sailboat is presented. The concept consider the volumes and weights of the Vismara V50, the first full hybrid boat. The performance of the H2Boat system are compared with the original ones, based on the lithium ion batteries technology. The considered system:

- 1 electrolyzer of 500 Nl/h;
- 1 fuel cell of 5-7 kW;
- 1 MH storage system of 50 kWh.

A comparison has been evaluated considering the same boat dimension, the results are presented in Table 65.

	H2Boat	Lithium Bat	
Energy	50	25,8	kWh
Weight	195	570	kg
Volume	360	260	l

Table 65. H2Boat vs Lithium system

Thanks to the exploitation of the keel to store hydrogen, large amount of energy, up to 80 (kWh) can be stored with minimum modification to the keel bulb, Figure 102.

The large availability of energy storage makes convenient the intensive use of renewable (solar, wind, hydro). Six 100 (Wp) PV panels, a sea generator propeller of 500 (Wp) and a 300 (Wp) wind generator are able to produce an average energy of 6.5 (kWh/day).

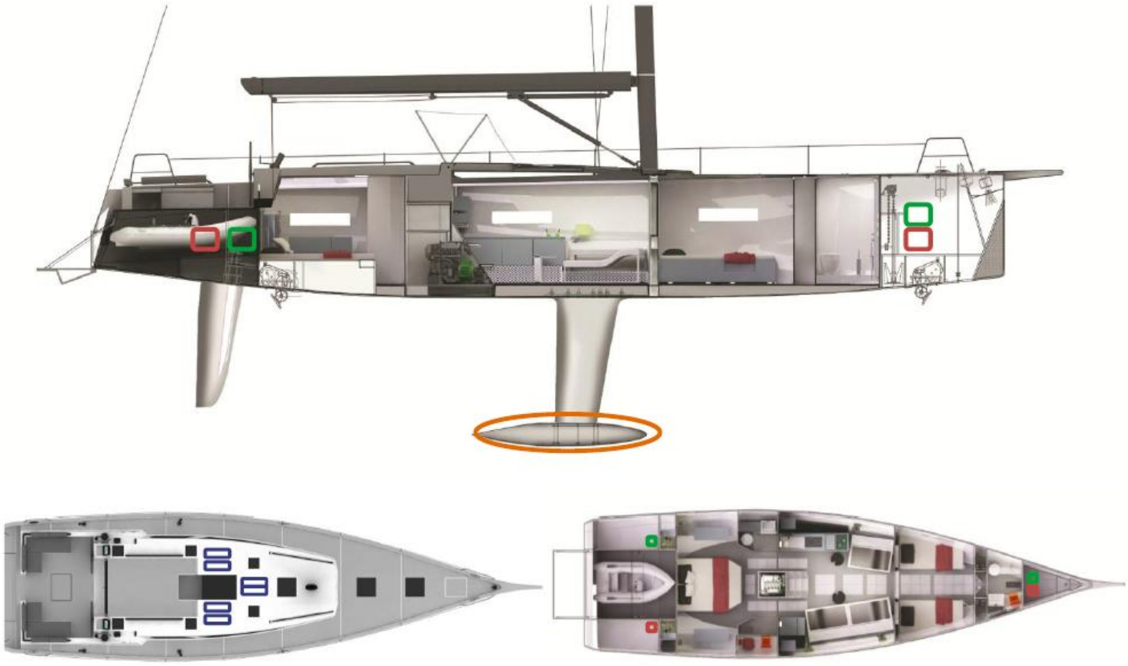


Figure 102. Vismara V50 H2boat concept

5. Conclusions and future activities

A broad variety of alternative fuels have been assessed with the goal to define the specific characteristics of hydrogen as alternative fuel for shipping. Indeed, hydrogen technology can be considered as such only if hydrogen produced by renewable sources is considered. Other solution can be technically considered interesting to reduce ship emissions and increase the on-board comfort, but are not able to fulfil GHG emission reduction. Moreover, fuel cell system solutions with fossil fuel based alternative solution result to be economically not competitive with ICE systems. The reason lay on the possibility to have ICE with Dual Fuel solution that permit the use of expensive alternative fuels only inside ECA zones and rely on traditional FO and exhaust gas treatment system during the rest of the time.

The study analysed the performance of fuel cells, in particular of PEMFC and HTPEMFC because are considered the most promising solution for the short-medium terms. The assessment has been followed by a detailed analysis of the FC BoP in order to define a standard configuration of a FCS. The work will help naval architects and rule makers to define the correct technical context in which the system should be integrated.

In any case the alternative fuel future marine use aboard ships will be surely start in conjunction with ICE rather that fuel cells. For this reason, the combination between LNG, LPG or Methanol with reformer and fuel cells or directly with fuel cells cannot be considered a real alternative to the fulfilment of IMO SOx and NOx emissions limitations. NOx emission reduction though is not a sufficient condition to switch from ICE to fuel cells, neither the reduction of noise and vibrations.

On the contrary, the future presence of these alternative fuels on-board ships will promote the use of fuel cells on this ships since one of the largest obstacle to fuel cell introduction, fuel storage, would have been reduced.

From the fuel cell SOA analysis, other limitation have been found concerning power size mainly, that together with costs and fuel storage limit the introduction of this technology in the maritime sector. For this reason fuel cell systems will be considered able to power APUs dedicated to AUX systems and low speed operative conditions on-board ships, at least during the short-medium term. The union of these two statements, namely LNG, LPG and Methanol performance with ICE and fuel cell systems power limitations, together with the above considerations, brought to the following:

- LNG, LPG and Methanol are able to substitute FO completely as well as to permit the compliance of IMO ECA emission limitation if used inside ICE equipped with EGR or SCR;
- Hydrogen, whatever the energy medium (CH2, LH2, MH) is effective only in conjunction with fuel cells;
- Fuel Cells Systems fuelled with LNG, LPG and Methanol do not represent an alternative solution to the IMO ECA emission limitation compliance due to the less expensive ICE solution;
- Hydrogen could represent an alternative solution to the IMO ECA emission limitation compliance as APU but result to be economical not convenient;
- SOFC are considered to be the future long term solution in conjunction with LNG storage;
- PEMFC module derived from automotive and land application represent the most promising technology to power FCS for marine applications.

The ambitious goal of the Hydrogen for Ship research program is the definition of the most feasible technical and economical solutions for the application hydrogen technologies on-board ships. The "Idea" is well represented in Figure 103. Starting from the ship requirements, following the scheme it will be possible to define the most suitable solution for hydrogen technologies in order to respond to specific driver requirements mainly imposed by the regulations. Figure 103 represent the first tentative to define the technical and economical boundaries of these applications for the short-medium terms. In order to complete and better define the scheme, further information should be collected and elaborated into the comparative models in order to define all the possible alternative power generation and energy storage configurations.

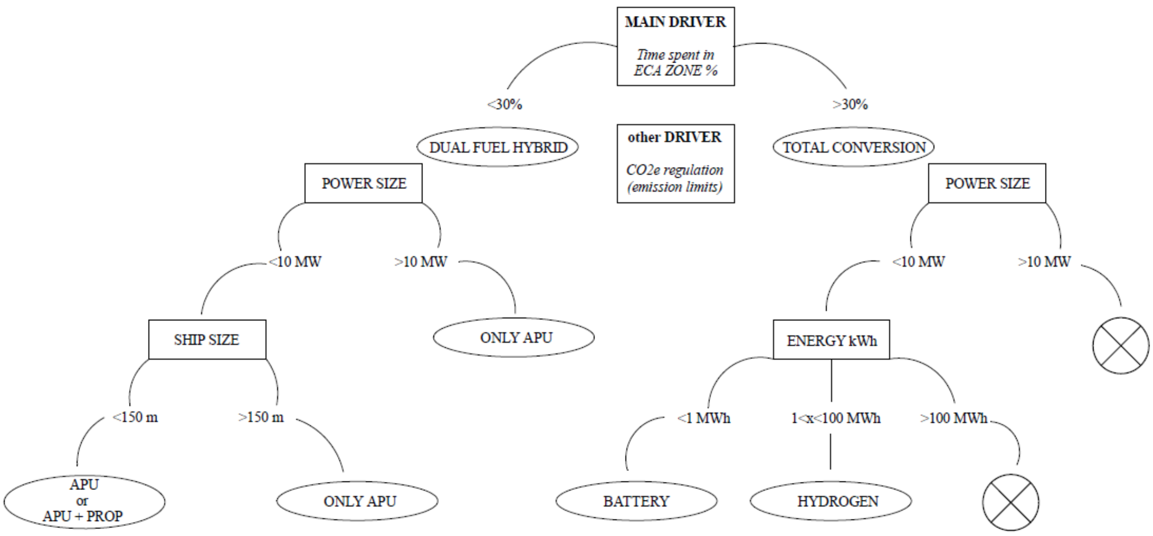
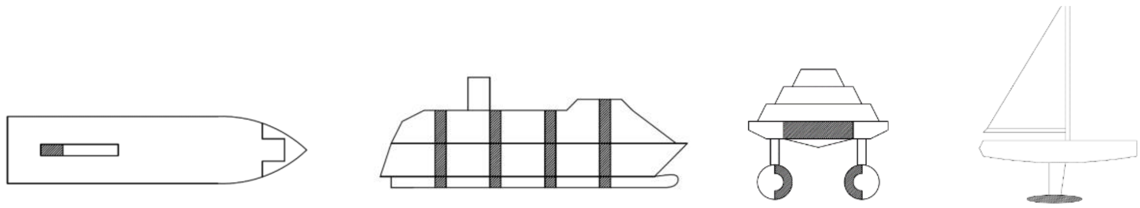


Figure 103. H2 solutions scheme (first tentative)

The scheme in Figure 103 start from the definition of the main driver requirements (ECA zone, CO2 regulation, local emission reduction, other) and the effect that they have on the examined ship. An important distinction is made between ships that spend most of their time inside ECA zones (>30%) and ships that on the contrary are prevalently outside ECA zones. The first will look for a total conversion while the second could look for a dual fuel solutions. A distinction should be made on the maximum installed power. 10 MW has been considered a technical limit for PEMFC systems. The distinction is different for total ship conversion or for hybrid solutions. The scheme propose different applications in terms of APU or APU+Small propulsion depending on the ship dimension for dual fuel systems, while the role of hydrogen is defined inside a definite energy range for total conversions.

During the PhD program though, there had been the possibility to test the tools under construction: H2 solution strategy scheme, comparison models, H2 solutions design. Chapter 4 reports the most important applications of the defined design tools. Table 66 shows a short resume of the hydrogen solutions that have been developed, divided for ship kinds. It is possible to observe the congruence between the H2 solutions scheme, the comparison model results and FCS design that have been proposed. At the end of the project it will be possible to derive more hydrogen alternative solutions with a good confidence on the relative applicability of it against other solution not based on hydrogen technologies.



RO-RO Ferry			Passeger Ship			Mega Yacht			Sailboats		
PEMFC	1.25	MW	PEMFC	10	MW	PEMFC	1	MW	PEMFC	1	kW
MH2 or CH2 on mobile container	50-100	MWh	CH2 or LH2	100	MWh	MH2 or CH2	50	MWh	MH2	30	kWh
Specific Ports			Logistic base			Electrolyser container			Electrolyser+RES		
			HTPEMFC	10	MW						
			MeOH	100	MWh						
			Logistic base								

Table 66. Hydrogen Technology ship application examples

The project presented in Table 66 are briefly explained:

1. The first solution has been designed for Ro-Ro ferries and still is under development. The ship target was defined on the base of the context analysis mainly derived from the influence of the alternative solutions drivers analysed in Chapter 1.1: Climate Change that drive Emission Regulations. In particular, SSS has been identified as a higher-level target for State Administration as it responds to many important requirements given by the "Climate Change" pressure driver:

    - Emission Reduction
    - Local Emission reduction (Ports)
    - Ports pollution (Health)
    - Ship age
    - Internal waters

    Moreover, the production of hydrogen by electrolyser require huge amount of electric energy. It is an author belief that the hydrogen production for ships could be used as energy storage to help the balance of the electric grid and the economic operation of large power plants (102) (103). For this reason the Ro-Ro solution under development consider a containerized mobile hydrogen storage, charged in ports and loaded on trailers. This solution could also be applied to already existing ships and will represent the main goal of future studies for short term applications.

2. Passenger ships on the contrary, are considered a mid term application because require larger energy storage. The former can be achieved only using LH2 or Methanol. The first solution though, result to be better if the efficiency of PEMFC and HTPEMFC is considered. Table 67 shows a comparison between the LH2 and Methanol solution. (Methanol solution require the storage of a similar amount of deionized water since the HTPEM fuel cells with reformer works with 50-50%vol mixture).

		MEOH	H2O	tot MeOH	CH2	LH2
ED	kWh/l	3.62	-		0.57	1.33
SE	kWh/kg	5.03	-		0.73	2.11
Energy	MWh			1000		
V	m3	276.0	276.0	551.9	1755.0	750.2
W	t	198.7	276.0	474.7	1379.2	473.7
ETA	%			25%		50%
EN. El	MWh			250		500

Table 67. LH2 vs MeOH solution for passenger ships

Nonetheless, important ship operators already announced the introduction of FCS of limited power (100 kW), that will mainly be used to show-off the innovative solution without really influence the ship energy balance. The study for the application of hydrogen technology on-board is still under development but important observation have been done in Chapter 4.2.4. At the present, an innovative design solution for the integration of LH2+FCS on passenger vessel is under study. The former consist in the definition of modular ship section of few meters to be inserted near the MVZ bulkhead covering the entire height of the ship, Figure 104. The design should permit the creation of continue volumes from the LH2 to the FCS guarantee the possibility to have safe passage to gas lines. Moreover the solution would comply with the distributed generation concept without alter the main ship design.

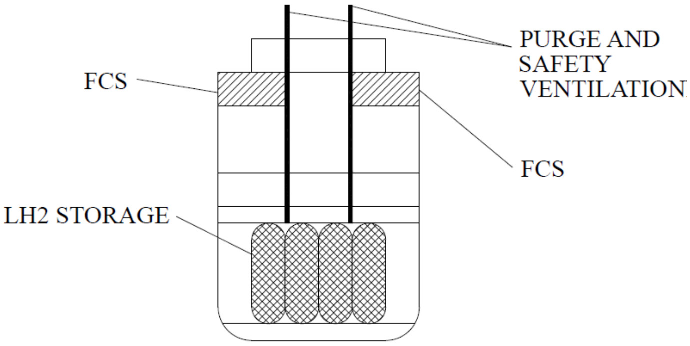


Figure 104. PAX ship LH2+FCS section

3. Mega yacht are an important hydrogen technology solution. The reason why they result attractive comes from the reduced influence of price and the increased importance of comfort and environmental friendly performance. It is thought that the MY75 totally respond to the characteristics of a yacht with the abovementioned requirements.
4. Finally the sailboat doesn't represent a ship application but an important niche market that could spread the use of hydrogen solutions in the nautical sector enhancing the awareness of this technology.

But the Hydrogen to Ship project will offer another important design tool. The already developed comparative models and energy vector analysis presented in this thesis are already able to partially provide it. Table 68 represent the first tentative of calculation scheme to size and assess different power solution. Starting from the definition of the ship requirements, the scheme give indication of cost and emission of the available alternative fuels. Once the fuel is chosen, following the path indicated in Figure 32 it is possible to assess the dimension (volume and weight) and costs of all the power system components (Storage, Generator, Fuel Treatment, Exhausts) making use of the Energy Density, Specific Energy and Specific costs defined inside the comparative models.

Section	Tool	Drivers		Output		
SHIP	H2 solution scheme	%ECA		FCS Power	x	kW
		CO2		H2 Energy	y	kWh
		Power				
		Energy				
FUEL	Comparison Model	$/kWh				
		kg/CO2/kWh				
		S%				
STORAGE	Comparison Model	y/ED		volume	l	
		y/SE		weight	kg	
		y*C1		cost	$	
GENERATOR	Comparison Model	x/ED		volume	l	
		x/SE		weight	kg	
		x*C2		cost	$	
FUEL TREATMENT	Comparison Model	x/ηFC/PD		volume	l	
		x/ηFC/SP		weight	kg	
		kg/kWh	H2O			
		kW/kW	ele			
EXHAUSTS	Comparison Model	x*weight	tot	weight	kg	
		x*volume	tot	volume	l	

Table 68. System performance calculations scheme

5.1 Publications related to the PhD studies

In the following the publications related to complementary side projects are reported. The former have been developed during the PhD study as in-depth analysis conducted in collaboration with Fincantieri or other University Department of particular marine applications of the hydrogen technology that has been the core subject of the doctorate course study.

APPLICATION OF FUEL CELL SYSTEM AS AUXILIARY POWER UNIT ONBOARD MEGA YACHT VESSELS: A FEASIBILITY STUDY

T Lamberti, L Magistri and **P Gualeni**, UNIGE, Italy; **A Da Chá** and **A Calcagno**, Fincantieri, Italy

SUMMARY

The present paper proposes an outline layout for the integration of Fuel Cells (FC) as Auxiliary Power Unit (APU) source for application on board a Mega Yacht. The assessment of the applicability of an on board Fuel Cell system has been carried on in order to identify the implications in terms of necessary space and therefore the suitable vessel size in which the system could be installed. The investigation has also focussed on the most profitable operational conditions in which the system onboard could be used. The study includes the assessment of different Fuel Cell technologies as well as of different Hydrogen Storage systems in order to find the best compromise that suit the requirements. A technical sizing of the FC system to be installed on-board the ship has been created together with the study of its dynamic performance using as a reference the Nuvera Proton Exchange Membrane (PEM) fuel cell data. The spaces for the installation of the FC system and the Hydrogen Storage system has been evaluated. Finally an assessment of the installation technical impact on the ship has been made and a range of possible solutions found. The feasibility of the proposed design has been tested starting from Liquified Natural Gas (LNG) fuelled Mega Yacht concept provided by Fincantieri Shipyard.

1. INTRODUCTION

In the latest decade a growing interest in air pollution reduction has emerged in the maritime community. This is due also to the intents safety rule making activity on this matter [1]. Among the different possible solutions to this problem, the technology of Hydrogen based power generation is one of the most interesting and challenging [2]. The Governments activity in producing tight rules and emissions limitations [3] on Internal Combustion Engine (ICE) and gas fuelled turbines is more and more demanding, therefore a growing interest in fuel cells technology is evident in literature and applications.

The great advantages of fuel cells are mainly the extremely reduced environmental impact, almost zero on site and a very low noise production. Furthermore FC have high efficiencies and they give the possibility to cogenerate, as the secondary product is hot clean water. This characteristics would be exploited more and more as Fuel Cell Technology improves, but mostly as Hydrogen Storage Technology improves. At present this technologies can be used only at prototypical level, but in the next future they could represent one of the solutions to the energy challenges.

In the present paper an application study is carried out in the specific field of mega yachts. For this vessel typology in fact further motivations for FC exploitation are extreme comfort performances and possible permanence in protected marine areas.

2. BINDING FRAMEWORK

The first evaluation that has been made concerns compliance to rules regulations and to technical and political constraints. The aim was to find the platform in which the fuel cells could be installed and a typical mission suitable for FC usage. Furthermore a binding framework inside which the system will have to operate has been evaluated, taking into account a number of aspects. The very first assessments were based on pragmatic general considerations on the Fuel Cell Systems, well known and easy to be verified [4], that are:

- High Costs;
- Low Power Density;
- Lack of Infrastructures (mainly refuelling).

The aspects that have been taken into account are the following:

Platform. A FC system for marine application cannot be effective from an economical point of view [4], thus only prototypical systems without ROI (Return Of Investment) requirements have been considered. An excellent marine platform for this application is a Mega Yacht. This branch of marine industry has some peculiar features:

- It is highly customized case by case so that each yacht is unique, and also if it mainly uses well proven traditional technologies each yacht represent the prototype of itself resulting very expensive;
- Cost is less connected to a market value. Instead of that, the cost depends highly to customer “whims”;
- A broad spectrum of dimensions could be taken into account, from 50 *m* up to more than 130 *m* in length.

A specific case. The design of a Mega Yacht has been considered as reference case. To better evaluate the impact of the FC System on-board the yacht, it has been decided to preserve the main dimensions of the ship, without modifying the hull and the superstructure.

Operational Profile. The possibility to replace the traditional power generator system has been excluded on the basis of the above mentioned thoughts, namely High Costs, Low Power Density and Lack of Infrastructures. Thus the system has been thought as an APU:

- For special harbour operational conditions and for navigation/stand still in restricted pollution areas.

FC System Dimensions. Starting from the Operational Profile of the reference yacht a number of data that influence the dimension of the system have been extracted, mainly the maximum power required and the endurance. The storage system has been sized on the base of the available onboard spaces while the endurance (days of continuous operation) has been found as consequence. The FC system's physical dimensions depend from the Fuel Cells' performance, therefore the dimensions of the room in which the system is meant to be installed resulted to be linked to the disposition of the system components. Special care has been used in order to reduce as much as practicable the impact on living areas, the most important feature in such kind of vessel.

Regulation. The yacht project will comply with the appropriate regulations of Administrations and the Classification Societies [5], that are very severe regarding on-board gas storage. As a matter of facts, ships which uses Natural Gas (NG) as fuel deal with similar problems, also if on a lower scale. A flowchart of the study's logic is showed in Figure (1). Actually it is not possible to use gasses as fuel except for LNG where the IMO Resolution [6] is adopted.

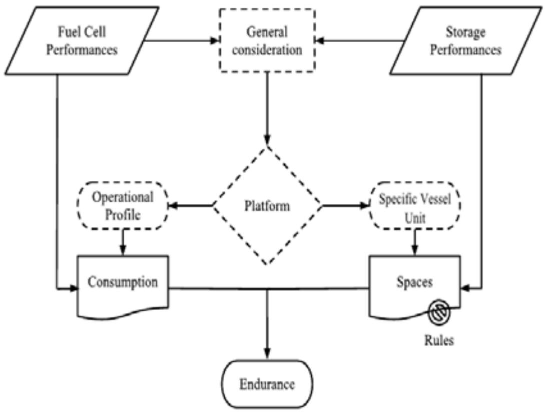


Figure 1: Flowchart

3. REFERENCE DESIGN

As a reference for this work a 99 *m* bi-fuel yacht concept design, called XProject, has been taken into account. The peculiarity of this hull is the capacity to be fed by traditional Diesel oil or by environmental friendly LNG. The original design has been provided by Fincantieri Mega Yacht Business Unit, that is investing a lot on this field. LNG is stored by two large tanks able to carry 90 m^3 each. The main dimensions of the platform are shown in Table (1).

$\boldsymbol{L_{BP}}$	99 m
$\boldsymbol{B_D}$	17.2 m
$\boldsymbol{T_D}$	5 m
$\boldsymbol{\Delta_D}$	abt 4500 t

Table 1: Xproject main dimensions

4. RULES AND REGULATIONS

In order to identify the suitable spaces for the installation of such systems an assessment of the available spaces on the XProject general arrangement plan that could comply with the rules has been developed [5][6][7]. The original project was already designed taking into account large storage bottles for LNG. All reasonable FC technological solutions have been tested. The general limitation imposed by the safety rules for Natural Gas fuelled ships have been taken into account [8], since specific rules for hydrogen fuelled ships are still lacking [9]. Some of the principal and more challenging rules are reported [6]:

- Maximum working pressure in enclosed spaces and in all the local under the main deck is of 10 *bar*;
- Spaces in which gas storage tanks are installed are not to be adjacent to accommodation spaces, service spaces or control stations;
- Spaces in which gas storage tanks are installed are to be separated from machinery spaces by means of a cofferdam of at least 900 *mm* in width;
- Spaces in which gas storage tanks are located are to be as close as possible to the centreline of the ship. As a minimum, they are to be the lesser of B/5 and 11,5 *m* from the ship side; the lesser than B/15 and 2 *m* from the bottom plating; but not less than 760 *mm* from the shell plating anywhere.

5. FUEL CELL

Fuel cells are electrochemical devices able to convert the chemical energy of a fuel (typically hydrogen) directly into electrical energy without the intervention of an intermediate thermal cycle and consequently allow conversion efficiencies higher than those of conventional engines [10]. There are different Fuel Cell technologies with different characteristics and different levels of development [10]. Usually, Fuel Cells are classified on the basis of the used electrolyte, Alkaline FC (AFC), Polymer Electrolyte FC (PEFC), Phosphoric Acid FC (PAFC), Molten Carbonate FC (MCFC), Solid Oxide FC (SOFC), or the operating temperature (low and high temperature). Generally the fuel cells work on the base of the same general reaction: $2\ H_2 + O_2 \rightarrow 2\ H_2O$ + electrical energy + heat. To compare the present fuel cells technology in order to find the one that better suits the required specifications, a Comparison Model has

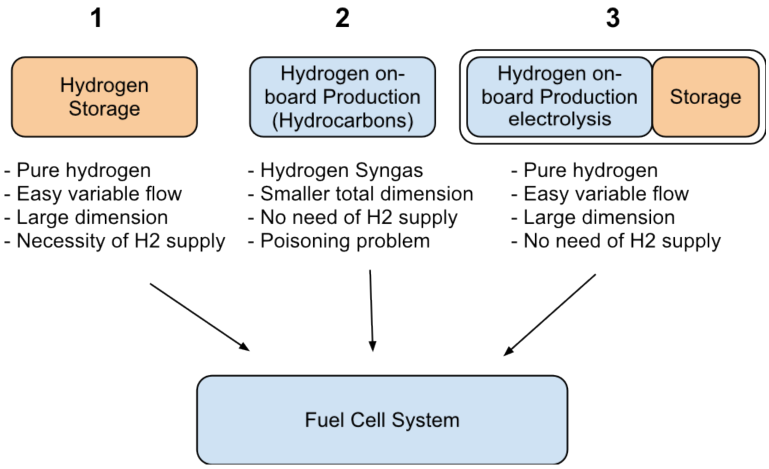


Figure 2: Fuel systems

been built. The fuel cell types that have been considered are the following:

- Polymer Electrolyte Membrane Fuel Cell (PEMFC);
- Solid Oxide Fuel Cell (SOFC);
- Direct Methanol Fuel Cell (DMFC);
- Acid Doped Polybenzimidazole High Temperature PEM (PBI PEM).

The decision to build a comparison model to study the differences between the different FC technology and to better understand their capabilities and limitations, rises from the consideration of the fact that it's difficult to compare different technologies when there are so many factors related one to another and each of them could be an advantage or a disadvantage as the case. The comparison model could be considered as a "spatial model" [11] in which the quality of the fuel cell is evaluated by the distance from the ideal condition, represented by the maximum evaluation in a system of points [13]. A series of characteristics have been investigated and for each technology an evaluation has been given between excellent (2 points), good (1 point) and not good (0 points). An example of the evaluation of some characteristics is reported in Table (2a). Such table is a partial overview of the entire analysis which took into account forty peculiar characteristic points, i.e. fuels, tolerances, and others.

Technology	PEMFC	SOFC	DMFC	PBIPEM
Start-up time	2	0	2	2
CO tolerance	0	2	0	0
Power density	2	0	0	1

Table 2a: Example of FC Characteristic evaluations

Results in Table (2b) show that there's not a best Fuel Cell Technology for all purposes but special consideration must been made for a correct choice.

Through this model, high power density, low temperature and fast start-up have been the key factors that leaded to the choice of the PEMFC technology as the best one for an APU application.

Technology	PEMFC	SOFC	DMFC	PBIPEM
Evaluations	29/40	26/40	22/40	26/40

Table 2b: FC Comparison Model final results

6. STORAGE

The fuel to be used in fuel cells for such kind of applications must possess technical and safety features such as to enable performance and functionality at least similar to those of a conventional fuel [4]. It requires:

- Energy density as high as possible, so that weight and dimensions on board are minimized;
- Ease of production, storage and distribution;
- Wide availability and reasonable costs;
- Toxicity and hazard equivalent to that of traditional fuels.

It must be noted that the choice is determined not only by technical factors but also by evaluations of energy policy. The ideal fuel for the polymer electrolyte fuel cell PEMFC is hydrogen, which ensures the best performance under specific conditions and allows to realize a relatively simple propulsion systems able to ensure an environmental impact practically equal to zero in the site where it is explored [4]. Currently the use of hydrogen on a large scale presents problems associated with its availability at low costs, with the storage systems on the vehicle, with the creation of a suitable distribution infrastructure and with safety and acceptability aspects from the user side [12]. In a vehicle powered by fuel cells, hydrogen can be stored on board (Hydrogen storage) or produced by other fuels (methanol, gasoline, Diesel) through a reformer installed on the vehicle (Onboard Hydrogen Production) [13]. It is believed that the direct use of hydrogen is at the moment the preferred solution [14] because of the difficulties related to the

phenomena of poisoning of the PEMFC by CO and SH_2 (with tolerances of the order of < 10 *ppm* CO and <1 *ppm* S_2 for typical MEA) generally present in the syngas produced from fossil fuel [15].
A third way could be an on-board electrolysis production of pure hydrogen coupled with a storage system. This system would eliminate the problem of hydrogen supply and all the technical and safety issues connected with tanks refuelling but not the issue related to hydrogen storage. A scheme of the available hydrogen storage systems is shown in Figure (2). Hydrogen has a high energy density per unit mass, but a low energy density per volume compared to hydrocarbons as shown in Table (3), thus requiring larger tanks for its storage compared to current standards.

Fuel	*MJ/kg*	*MJ/l*
Gaseous H_2	141.9	0.01
Liquid H_2	141.9	10.1
H_2 (700 bar)	141.9	5.6
Diesel	46.2	37.3
Gasoline	46.4	34.2
Methane	55.6	0.04
Methanol	19.7	15.6

Table 3: Fuel energy densities

Among a series of available technology the following ones have been considered:

- Compressed Hydrogen Storage (CH2);
- Liquid Hydrogen Storage (LH2);
- On-board Hydrocarbons Reforming (STAR);
- On-board Electrolysis (EH2);
- Cryo-Compressed Storage (CCH2).

As far as metal hydrides are concerned, they have been left apart because of their high weight and low transient response, connected to the complexity of the storage system. Nevertheless this technology is actually the only one used for Naval applications [16]. A Comparison Model has been developed in order to compare the characteristics of the Fuel Systems with the same structure of the one built for the FC comparison, in order to find the best solution for APU applications [13].

Technology	CH2	LH2	STAR	EH	CCH2
System weight	1	1	2	0	1
System volume	0	1	2	0	1
Fuel availability	1	0	2	2	0

Table 4a: Example of FC Characteristic evaluations

An example of the evaluation of some characteristics is reported in Table (4a). Such table is a partial overview of the entire analysis which took into account about thirty peculiar characteristic point, i.e. efficiency, complexity and others. The result has been that, Table (4b), if on-board hydrocarbons reforming like the STAR (Substrate Transportation Autothermal Reformer, a Nuvera property fuel processor system) will prove to produce a sufficient clean hydrogen flow there is no doubt about its possible future use for marine applications. But if STAR system is excluded, there is no clearly preferable storage option [17].

Technology	CH2	LH2	STAR	EH	CCH2
Evaluations	11/28	10/28	17/28	10/28	11/28

Table 4b: Storage Comparison Model results

The graph in Figure (3) shows the volume of the storage system versus the energy stored among growing size STAR reformers and the CCH2, the most performing pure H_2 storage system considered; the large difference is due to the different hydrogen concentration between fossil fuels and physical hydrogen storage systems.

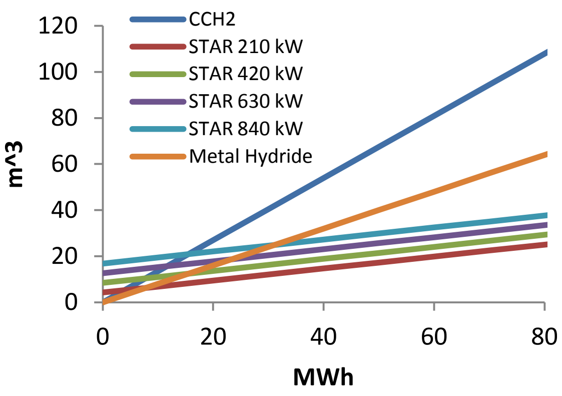


Figure 3: STAR vs CCH2 volume density

There is actually 61% more hydrogen in a *litre* of petrol (116 *grams* of hydrogen) that in one *litre* of pure liquid hydrogen (71 *grams*). Otherwise, the only way to use fuel cell on-board a ship will be to store pure hydrogen through one of the other described systems as the present situation requires. For very small application (< 500 *kWh* of energy storage) CH2 is the best choice, because of the lower complexity of the system. Otherwise the competition is continued by LH2 vs CCH2 and vs EH2 systems and eventually metal hydrides. Considering an annual consumption of about 990.6 *MWh* [17] and the harbour condition as better defined later, it means that for an endurance of about 15 *days* the storage system should be able to store an average of 40 *MWh*. For this condition, also under the hypothesis of the availability of the STAR system, the complexity of the reformer system could make other solutions convenient.

7. CONCEPT DESIGN

The fuel cell system is composed by two main components: the power generation system (fuel cells, batteries and converters) and the storage system.

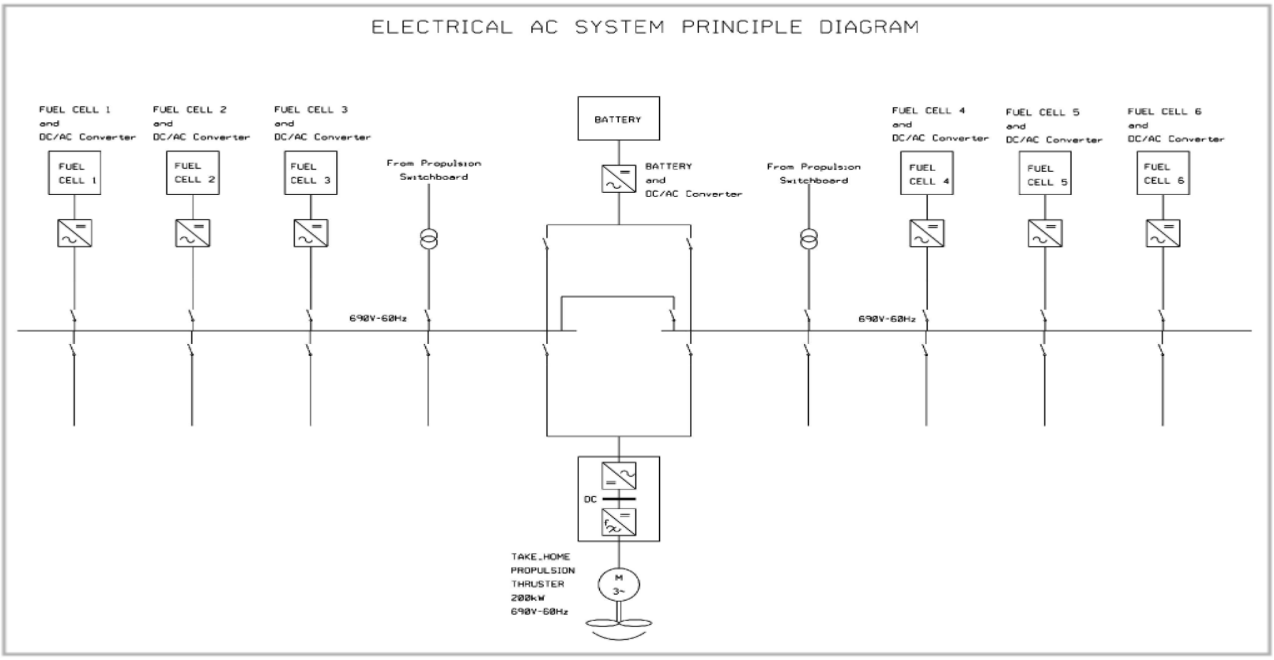


Figure 5: Electric scheme

7.1 POWER GENERATION SYSTEM

The power generation system is composed mainly by the FC modules, the batteries and the converters, to whom all the necessary auxiliary systems must be added. The system has been sized on the maximum power required, which is the sum of the power required from Hotel services in the Harbour operational mode 800 *kW* [18], plus a fraction of power required for a low speed propulsion system estimated of 200 *kW* together with an energy buffer necessary to cover occasionally limited power request estimated of 200 *kW*, with a energy storage of 100 *kWh*. Since the Fuel Cell System is mainly called to feed a demand that operates at 690 *V* 60 *Hz*, a direct connection with the two original azimuthal propeller has been discarded. The ship is supposed to be moved up to a maximum speed of about 5 *kts* through a retractable bow steering thrusters. From the FC Comparative Model the best fuel cell technology appeared to be the PEMFC, so this technology has been considered. A preliminary study of the volume and weight of a fuel cell module for marine application has been prepared in order to be able to reproduce an hypothetical ad-hoc module of 210 *kW*. The Fuel Cell technology is already used in a variety of fields, among them it has been chosen to refer to the naval application applied onboard the U212 submarine of the Italian and the German Navy [16]. The marinization of the components considered the following factors:

- Vibration;
- Humidity;
- Salt Air;
- Noise.

A stack made up of 150 fuel cells for a maximum power of 39.3 *kW* has been taken into account together with a Simulink Matlab® dynamic model [13][19]. The purpose of the dynamic model was to verify the dynamic response of the fuel cell to typical marine electric load profile. A real load assessment of a Mega Yacht has been considered [16][20], together with other different load scenario. The main achievement has been the assessment of the capability of the fuel cell to supply the required power without the necessity of an auxiliary battery pack for the limited power peak control (100 *kW*), Figure (4) shows the dynamic response of the Simulink model.

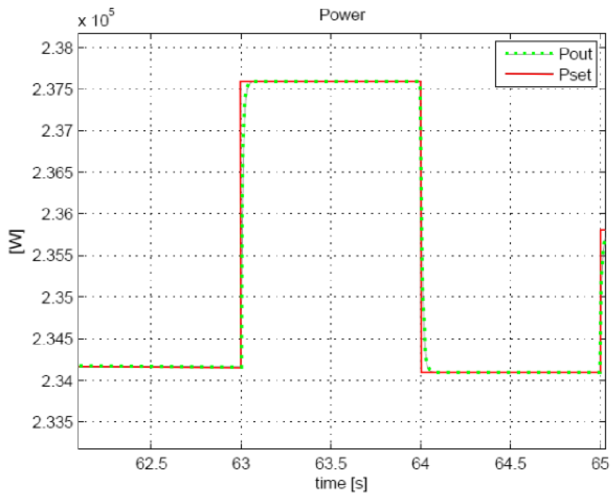


Figure 4: Dynamic Model

Thanks to the performed evaluation, it has been possible to size the battery pack power to 1/5 of the total FC system power, with the only task to ease the fuel cell control under critical situations. A total number of 6 fuel cell stacks has been packed together in series to obtain a module of 235.8 *kW* of maximum power for a physical dimension of 1x1.2x1 *m* and a power density of 235.8/1200 = 0.2 *kW/l*, Table (5).

Stack		Module	
# Cells	150	*# Cells*	900
I	400 *A*	I	400 *A*
V	98.3 *V*	V	589.8 *V*
P	39.3 *kW*	P	235.8 *kW*
Volume	28 *l*	Volume	1200 *l*

Table 5: Technical data

The electrical design scheme has been made on the base of the power requirements hypothesized, 800+200+200 = 1200 *kW*, 200 *kW* of which are provided by the batteries. It results that the number of necessary fuel cells (FC) modules is of 1000/210 = 4.7. For redundancy reason 6 FC modules has been considered. The battery consists of 112 elements each of 500 *Ah* electrically connected in series and installed inside a dedicated battery cabinet with dimensions of 2x0.9x1.5 *m* together with a bi-directional converter that has been designed to operate in parallel with the FC modules. Each module is coupled with a converter with an output of 690 *V* 60 *Hz*. An example of the possible electric scheme of the FC System [14] is reported in Figure (5).
In order to define the interfaces of the designed APU Fuel Cell system and to promote the related market entry, the mechanical integration of FC onboard a mega yacht by means of virtual 3D constructions has been made. This has involved the determination of volumetric constraints, mechanical and electrical interfaces as well as safety and security relevant issues.

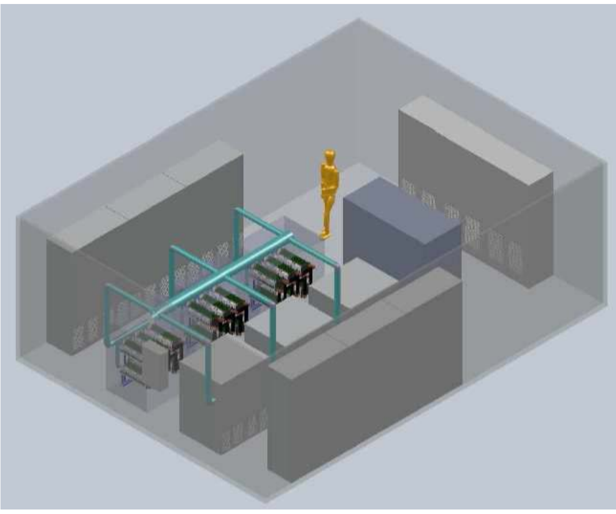


Figure 6: FC room

A 3D model of the FC room is shown in Figure (6). To complete the study of the FC System all the following auxiliary systems have been analyzed:

- Hydrogen supply system;
- Air supply system;
- Distilled water primary refrigeration system;
- Water reaction Collecting system;
- System for the removal of residual gases;
- Nitrogen supply system;
- Monitoring and control systems;
- Discharge resistor;
- Retractable azimuthal propeller.

All the above mentioned systems have been successfully integrated on board. It must be noticed though that the Air supply system requires large volumes for the piping and for the presence of several air compressor units since the air flow is estimated to be 0.23 kg/s just for one FC module, large if compared to the one of hydrogen 0.007 kg/s [10].

7.2 STORAGE SYSTEM

The storage system has been evaluated as a function of the available spaces able to comply with Classification Societies' rules and with technical constraints [5][6][7]. From the Storage Comparative Model it resulted that there's not a leading storage technology, excluding the hydrocarbon reformer. Thus all above mentioned technologies have been considered in different schemes since they have their own peculiarities. Starting from the original XProject design, 5 different areas have been identified with different installation arrangements. Due to rules constrains the installation of all the considered types of storage technology is not permitted in all the zones. An important distinction could be made between the storage systems that operate with fuels under pressure lower than 10 *bar* and the ones that operate with higher pressure values. The first ones could be installed under the weather deck, the second could not as shown in Figure (7). The spaces' assessment has been made for the identification of the storage system dimensions and it has

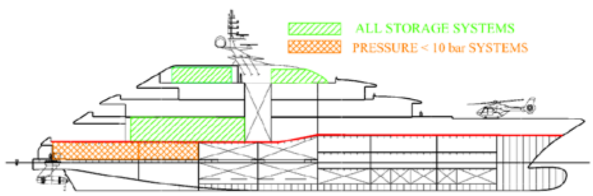


Figure 7: Installation Rule constrains

been also useful, as for the preliminary analysis, for the identification of the available volumes for the installation of both the power generating system and the storage system. For what it may concern the evaluation of the structural impact, the total weights of the FC system components are of about the same order of magnitude (or

Mission	Operation Mode	% *h/year*	Hydrogen *t/year*	*MWh/year*
Charter	Port	20%	3.9	67.6
	Fast at Sea	0%	0	0
	Cruise	0%	0	0
	Harbour	100%	52.4	903
Crew Only	Range at sea	0%	0	0
	Shipyard	0%	0	0
	Port	0%	0	0
Manoeuvring	Manoeuvring	10%	1.2	20
Totals			57.5	990.6

Table 6: Hypotesis of use

smaller) of a typical ICE system, so that a dedicated re-design is not required at this stage. For what concern the tanks, the original LNG system maximum total weight is of about 100 *t*, and the average hydrogen storage weight result to be of the same order. This aspect could require a more detailed structural analysis for the configurations that takes into account the installation of the systems on the superstructure. This analysis has been omitted in this work.

8 PRELIMINARY ANALISYS

Thanks to available data it has been possible to assume an operational profile of a typical yacht of the same size of the investigated one. From this profile it has been possible to evaluate eight different operational scenarios, each of them requiring a different power demand. Generally it is possible to split the required power in the Hotel Load and in the Propulsion load. The higher power demand comes from the Propulsion system, but it has been supposed to use the Fuel Cell system just for low speed navigation in restricted areas. Hence the main operational mode that the system is called to meet is the Harbour mode. This operational mode consists on the loads required by the ship when it is at the anchor near the coast. It has been supposed to use this system to enable the ship to enter areas that otherwise would have been prohibited to pollutant ships, such as particular marine protected areas or ports. It has been also considered a small fraction of propulsion energy demand to permit the ship to enter and exit the restricted area.

Storage systems	*l/kWh*	*Kg/kWh*
CH2(350 *bar*)	3.26	0.97
LH2	2.49	1.04
CCH2	1.35	1.06
Diesel	0.26	0.22
Hydride	0.8-1.0	2.4-2.9

Table 7: System storage performances

Finally a small energy demand for the Charter port operation mode has been considered, just to take into account the possibility that the FC system can be used for showing off. The Table (6) shows the percentage of FC system usage for each operational mode as described before in order to determine the total energy required for a year, equal to about 1 *GWh/year*. The Hydrogen necessary quantity has been calculated considering the specific consumption of commercial fuel cells. The estimation has been made taking into account one year of operation. The hypothesis made on the performance of the storage system and the fuel cells are at the base of the assessment. The considered storage performances data showed in Table (7) have been evaluated from DOE studies and refer to the volume of the tanks [21]. By kgH_2/l is meant the external volume of the tank that consist of a thin layer of carbon based material for what concern CH2 tanks and a more complex tank wrapped by insulating material for LH2, CCH2 system involves the use of a LH2 vessel for the storage of liquid hydrogen at cryogenic temperature that can stand high pressure like CH2 vessel [22]. It must also be considered that not all the available volume of the room can be used because maintenance and human factor volumes must be taken into account. For CH2 a large tank could be used to extend the energy density but a small one has the suitable characteristic to better fit the space and reduce the consequences of an eventual tank failure. For what concerns the LH2 and CCH2 tanks it must be considered that they're dynamic systems because of the tendency of the liquid hydrogen to evaporate and transform itself into a gas state (3-4 % day boil off). For this reason it's very important to keep the temperature constant, and to do that a larger mass can help. From a comparison analysis with the original concept design [23] it results that only 45% of the gross room volume could be occupied by the LH2 tank while about 66% is available for CH2 tanks. For LH2 tanks, the limitation is related with the sufficient height of the room because usually large cylindrical tanks are used. It must also be considered that the tanks for liquid hydrogen need a small system to vaporize the hydrogen before its use. This system is not considered in the net volume of the tanks but is taken into account in the energy density capacity of the system. For the evaluation of the CH2 configuration, a thorough analysis of the tanks dimension has been made. To consider a special storage of compressed hydrogen tanks the volume and weight of the total storage system have been evaluated considering the hypothetical containment structure. It has been considered a larger volume for the tanks space of about 1.5 *cm* per side and 10 *cm* more in length. The results are shown in Table (8) and Figure (8).

350 *bar* Tank	
L	1.6 *m*
B	0.565 *m*
H	0.565 *m*

Table 8: CH2 tanks dimensions

A first comparison between the storage systems capacity has been made. Thanks to a detailed assessment of the consumption of an hypothetical charter over a one week period, it has been possible to compare the results of the substitution of the original LNG complete system , with the best solution among the hydrogen storage technology, i.e. the cryo-compressed hydrogen storage

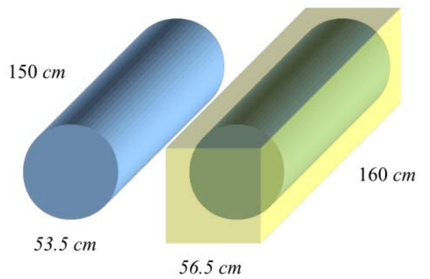


Figure 8: 350 bar Tank

system. Considering the same tanks dimensions and the same operational profile that requires a energy storage of 168 *MWh/week*, the different days of endurance guaranteed by each storage system are compared. It's worth mentioning that while the LNG system was thought to fuel the same bi-fuel engine ordinarily fuelled with Diesel oil, Hydrogen systems require a fuel cell to generate power that has not been considered in the values of Table (9). Each installation scheme has been further investigated in order to check the physical possibility to install every requested component: the fuel cells inverters, the battery and the battery converters will be installed.

Storage System	MWh/m^3	Endurance(days)
LNG	1.81	13.6
CCH2	0.74	5.6
Diesel	3.81	28.6

Table 9: Endurance comparison

On the basis of the hypothesis made before on the dimensions of the components, a footprint of 35÷50 m^2 is necessary for a suitable arrangement. From the results obtained is not possible to state that a technology is definitely the best one: each has pros and cons, and the final chose must be tailored case by case. Evaluations of system suitability also in terms of impact on ship stability, trim and displacement have been carried out. The results for each scenario are acceptable, meaning that the impact on the stability of the ship is not critical:

- **Displacement.** The difference in terms of weight between the LNG system (unloaded) and the FC one (loaded) is of ~100 [t], negligible compared to the unitary displacement.
- **Trim.** The trim evaluation is very satisfactory for each conditions, with an slightly attitude of trim by bow that might be considered acceptable.
- **GMT.** The metacentric height results good for all the conditions. While the GMT for the basic condition was of 0.99 *m* the lowest height found in this preliminary study has been 0.90 *m*, very acceptable.

9. CONCLUSIONS

Shipping contributes to global CO_2, NO_x, SO_x and PM emissions even if not covered by the Kyoto Agreement it will be strictly regulated by IMO emissions rules that are about to enter in service. Fuel cell technologies could be a solution for a partial or a total reduction of on site emissions. Large luxury yachts are seen as an ideal entry point to the off-shore market for this developing technology considering its current high cost. A comparison model of the various fuel cell technologies has been developed with a storage system comparison model, in order to evaluate the best technology available. This study investigated the feasibility of using a Fuel Cell system based on the PEM technology to drive the electrical base-load auxiliary systems as an APU. A SimulinkMatlab® dynamic model has been constructed to simulate the 210 kW FC module with various configurations to make a real time electric load assessment of a 99 m dual-fuel Mega Yacht project, provided by Fincantieri Shipyard. The load changes varies from ±30 to ±100 kW and the PEM FC is suitable to compensate these fluctuations reducing the need to install a buffer energy storage that has been anyhow considered with a battery pack in order to ease the FC control and to manage larger peaks of 200 kW. The Harbour Operational Condition together with a low speed propulsion system has been considered to size the FC System and the Storage System. A final analysis of the spaces where the system could be installed complying with the safety rules has been made together with the assessment of the design impact of the installation on the ship and an evaluation of the ship equilibrium waterline stability.

- Platform. The XProject results to be the right target for the application of a FC APU system in terms of available space but not as good in terms of energy requirement. The design of ships with FC systems should be taken into account from the very beginning, in order to better suits the safety rules.

- Operational Profile. The Harbour Operational profile does not consider propulsion, the most energy consuming system. The power considered for a low speed propulsion is far smaller than the one required by the propulsion system for the cruise speed, 200 *kW* against 3600 *kW*. Anyhow the required Hotel power is high, 800÷1000 *kW*. In order to reduce the environmental impact of the ship, the installation of a FC APU system is not enough; it is necessary to reduce at the same time the energy consumption by using special solutions on the ship design such as a well designed hull or more efficient cooling systems. This arrangements could also improve the endurance of the system.
- Regulations. From the assessment on the rules provided by the IMO, it results that the Marpol Tier rules will require a very stringent reduction of the ship emissions for a wide range of sea area, especially for the coastal area. This fact could increase the number of scenarios where FC may be a profitable source of power. The FC system though, has been designed as APU for technical reason and in unlikely to the original LNG system, it's not able to sustain the total power request of the ship. The FC system thus, cannot be considered as an alternative solution to the traditional one, at least for the moment.
- Fuel Cell. The Fuel Cell Comparison Model shows that for the A.P.U. application, the best fuel cell technology is the PEM, while for the ship total power generation the SOFC results the promising technology.
- Storage System. By the Storage Systems Comparison Model is possible to say that the use of a Diesel reformer like the Nuvera STAR system could be the best way to storage hydrogen. Since there is no evidence of the availability of such a system, an alternative should be considered. Other storage systems available are compressed hydrogen, liquid hydrogen, hydrides, and others, but as results of the comparison model, there is not a predominant technology and all of them suffer of the same low energy density problem.
- Technical impact. As results from the concept design chapter, there are not particular concern about the weights and the positioning of the system. On the other hand, the large required volumes together with the stringent rules create a hard binding framework in which is not easy to be integrated onboard.

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H2Boat: an hydrogen energy pack for sailing boat application

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Abstract

Hydrogen energy technology allows to produce electricity from hydrogen and backwards to store large amount of energy converting electricity into hydrogen, by means of a fuel cell, an electrolyser and a hydrogen storage system. The fuel cell market increased from 24,600 units in 2011 to 78,000 in 2012 offering components with improved converting performances [1]; the expansion of this market and the spread of hydrogen system applications is bringing down the industrial costs of such technology offering new opportunities for commercial applications [2]. This paper presents a technology assessment of an hydrogen based energy system for sailboat up to 40 ft. in comparison to traditional electrical accumulators. The object of this paper is to demonstrate the technical feasibility to install a hydrogen based Hybrid Renewable Energy System (HRES) onboard sailboat in order to improve comfort and safety in a total environmental friendly way by means of the analysis of an innovative system that integrates the renewable energy produced by PV panels, wind generator and hydro generator together with a hydrogen hydrides energy storage system, a water electrolyser, a fuel cell and a battery.

New regulation and the rising ecological sensibility in Europe need new clean technology to make green the European nautical market, the biggest one in the world counting 1.4 yachting boat per 100 inhabitants in Italy, and up to 2.2 in France [3].

Keywords: Hydrogen, Sailboat, Hybrid Power

1 Introduction

The hybrid propulsion concept as the electric boat concept are not new [16][17]. The reason why these systems are studied and developed are many, from pollution reduction to energy flexibility. One of the major challenge that prevents to this configuration to spread is due to the poor performances of the batteries. This is also the reason why the bonanza of renewable energy available on the sea is so poorly exploited by boats. Starting from the energy requirement of a sailboat of 40 ft., the present electrical energy generator systems state of the art has been investigated from renewable energy generators to traditional diesel engine, a comparison of the solutions has been done by means of the data extracted from the software WECoMP. The possibility to produce high quantity of renewable energy has been found together with the lack of an appropriate energy storage technology able to take advantage from it. An assessment of the application of a innovative fuel cell based solution called H2Boat and composed by electrolyser/fuel cell/metal hydride storage was analyzed underlining the possibility to provide clean energy both for the auxiliary and the propulsion system in a totally emission free way.

2 Onboard Electrical System

An electrical system is characterized by one or more sources of electrical generation, a system of distribution and utilities. Electricity can be produced by axis generators, solar panels or other renewable energy sources converters, fuel cells, etc. and stored in batteries. The distribution system onboard includes a the Direct Current (DC) and an Alternating Current (AC) line, in fact small pleasure boat, especially sailing boat are usually equipped with both system while the DC system is always active and coupled with an energy storage (the batteries), the AC distribution is often inactive and uses the energy produced directly by the generators. Utilities on board can be classified into three groups: *Main* or *Propulsion*, when there is the presence of an electrical motor; *Auxiliary* for lights and other small power utilities; *Special* for all the others.

3 Electrical balance

The ideal design tool required to develop an assessment of the energy balance onboard a ship in order to introduce innovative energy technology is the Electrical Balance. The Electrical Balance is usually divided in two parts, one for DC and one for AC systems. Normally the utilities consumptions are grouped together in services families as lights, navigation apparatus, ventilation, air conditioning etc. and considered for given Operational Conditions. In the following, two main conditions for a sailing boat are analyzed:

- Harbour
- Navigation

In order to make the results more realistic, two more different operational conditions have been considered:

- Cruise Navigation
- Day Navigation

Both conditions consider different mix of electrical supply/needs in two different sailing travels [4] as will be better described in the next paragraphs.

3.1 Operational Condition

After defining the operational condition of a sample 40 ft. sailboat a reliable electrical demand table was constructed [4], Tab.1 show the electrical power of the considered devices. Four operational conditions have been investigated: Continuous navigation (NAVIGATION 24h); Continuous harbour operation (HARBOUR 24h); Day cruise navigation 11h long (DAY CRUISE 11h); Cruise navigation 24h long (CRUISE 24h).

Table 1: Electrical power demand

Tool	Power [W]	Current consumption at 12 V [A]
Gps Plotter	3	0.25
VHF	5	0.42
Automatic Pilot	60	5.00
Anchor Windlass	1000	83.33
Instrument and Measurement	1.5	0.13
Navigation Lights	30	2.50
Anchor Light	15	1.25
Internal Lighting	60	5.00
Fridge	50	4.17
Fresh Water Pump	100	8.33
Radio	30	2.50
TV/Computer	45	3.75

3.1.1 Navigation

A sailing day was analyzed and an hypothetical electric load profile constructed supposing that the boat sails all-day long during the 24 hours. In this situation navigation lights and instruments were considered turned on for a long period during the day. The navigation was mostly supposed man guided while amusement devices were considered turned on for an average of 12 hours a day according to the rules which implies navigation lights turned on from sunset to sunrise, Fig. 1 shows the electrical load of Navigation profile. A table which describes the average utilisation factors of each devices during a typical day of operation is reported in Annex 1.

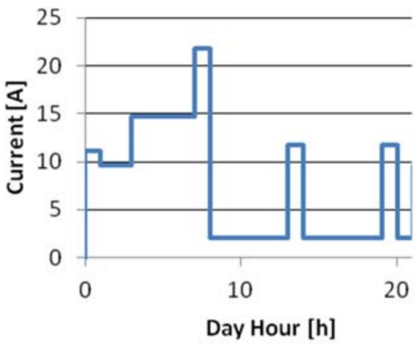

Figure 1: Navigation electric load profile

3.1.2 Harbour

A 24 hours of harbour condition has been analyzed and an hypothetical electric load profile constructed. In this operative condition navigation instruments and lights were considered turned off, while along the day a larger utilization of the amusement devices like TV and radio was considered, Fig.2 shows the electrical load of the Harbour profile.

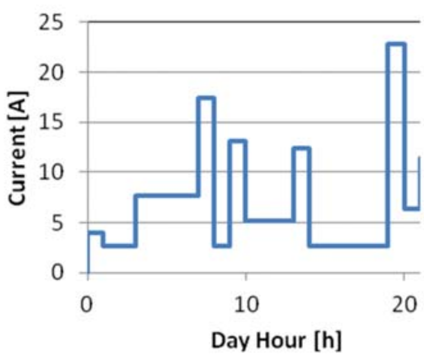

Figure 2: Harbour electric load profile

3.1.3 Day cruise

A combination of the previous conditions was analyzed and a daily trip operational condition of 11 hours has been assumed. In this case, it was considered that the boat leaves the port in the morning and sails for three hours to its destination where she stays still at anchor for 6 hours in harbour operative condition before coming back to port with another sailing period of three hours. All the sailing periods are man driven, without the use of the automatic pilot. All the boat electrical equipments are turned on in different moments of the day as shown in Annex 1, Fig.3 shows the electrical load of the Day Cruise profile.

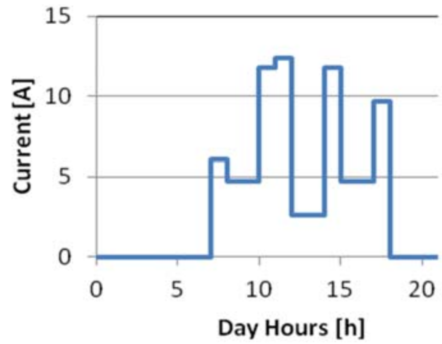

Figure 3: Day cruise electric load profile

3.1.4 Cruise

Another mixed situation has been studied and an all-day 24 hours cruise operational condition was assumed. In this case, it has been considered that the boat sails for six hours a day and stay still at anchor for the rest of the day in harbour operative condition. Also in this case the sailing periods are man driven, without the use of the automatic pilot and all the boat electrical equipments are turned on in different moments of the day (Annex 1), Fig.4.

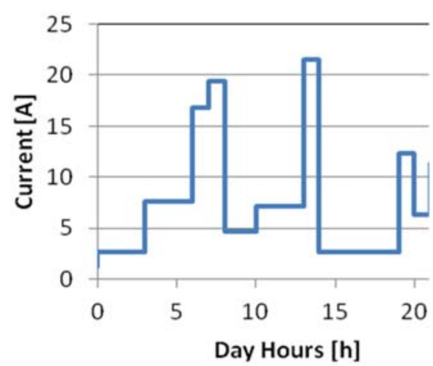

Figure 4: Cruise electric load profile

3.2 Energy Consumption

The operational profiles that have been supposed before took into account a number of approximations and hypothesis considering a general use of the boat in the different scenarios, nonetheless the operational profiles considered were validated by interviewing yachtsmen and leisure boat owners, and resulted significant and sufficiently reliable to proceed with the assessment of the power and energy matching between

renewable generators and the electrical boat consumptions.
The maximum power demand considering all the onboard electrical devices active is of 1400 W, while the daily average energy consumption for each operational condition is reported in Tab 2.

Table 2: Daily Electrical energy demand

OPERATIONAL CONDITION	Wh	Ah (12V)
NAVIGATION 24h	2233.7	186.1
HARBOUR 24h	2036.7	169.7
DAY CRUISE 11h	908.7	75.7
CRUISE 24h	2137.0	178.1
AVERAGE	1829.0	152.4

4 Renewable energy production

The sample boat is supposed to be equipped with two photovoltaic modules (100Wp for each module). a wind generator (300 Wp) and a hydro generator (500 Wp). To simulate the behavior of these generators three products available on the market were chosen. the details of each of them are reported in Tab.3. Tab.4. Tab.5.
Nowadays the potential renewable energy production can't be totally exploited due to the limited electrical storage capacity.

Table 3: PV panel technical features

Canadian Solar CS6C - 100 W	
Cell Type	Monocrystalline
Dimensions [mm]	1485x666x40
Weight [kg]	12
Nominal Power [W]	100
Optimum Operative Voltage [V]	17.3
Optimum Operative Current [A]	5.79
Operating Temperature	-40°C ÷ +85°C

Table 4: Micro wind generator technical features

Leading Edge - LE 300 Wind Turbine	
Rotor Diameter	1 m
Rotor Type	3 - Blade Upwind
Blade Material	Glass Reinforced Nylon
Peak Output	300 W
Cut-in Speed	3 m/s
Rated Output	85 W @ 8 m/s
Weight	8.8 kg

Table 5: Hydro generator technical features

Watt&Sea Hydrogenerator 500 W	
Power	120 W @ 5 knots
	500 w @ 8 knots
Start up Speed	3 knots
Weight	8 kg
Rotor Type	3 Blade Unit

4.1 Renewable generation

Since the electrical production depends from a time-dependent sources, a time-variable analysis that consider also the weather is needed to evaluate the renewable power production. To evaluate it, the software WECoMP (Web-Based Economic Cogeneration Modular Program) developed by TPG at University of Genoa for time-dependent thermo-economic analysis of poly-generation power plants was employed [6] [7]. WECoMP is characterized by a modular approach and a standard component interface, which allows the user to build complex cycle configuration in a short time. This approach maintains the flexibility and the extendibility of the library components (41 modules are available at the moment. from traditional and renewable energy systems) allowing the user to add new components without modifying the core of the code written in FORTRAN language. Each component is described by three subroutines. which define mass and energy flows. off-design performance curve. variable and capital costs.
In this study the Renewable Generator module (mod.22 in the software) was used (Fig.5). This module can calculate hour-by-hour the production of the generators thanks to their characteristic curve implemented in the main code and thanks to a file .txt containing the daily weather conditions.
For the PV generator a hour-by-hour production curve is implemented in the code. based on solar irradiation data in Savona (Liguria, Italy) given by the software METEONORM [8].
The characteristic curve of the wind generator in object (LE-300) [9] was matched with an average wind profile in the port of Savona [10] in a typical day of summer season.
The hydrogenerator production is calculated considering the performance curve of the chosen generator (WATT&SEA Hydrogenerator) [11] and

a random sailing speed profile, as the power production is tied to the speed of the boat bold.

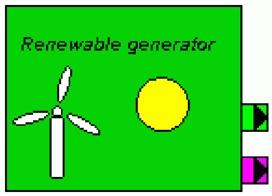

Figure 5: Renewable Generator Module in WECoMP Software

In each of the studied cases. there are different production profiles from the renewable generators as the hydrogen generator was considered works only during sailing period and the wind generator works only in the harbour condition. The PV panels work in all the situation. In Fig.6 the results of WECoMP simulations are shown. supposing to use each generator for 24 hours.

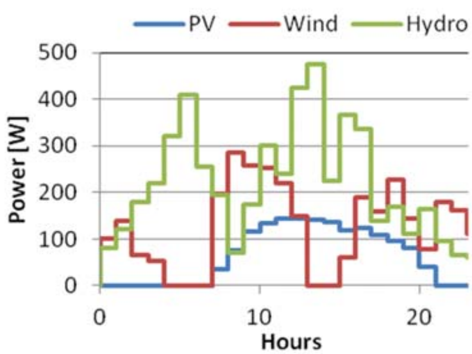

Figure 6: Renewable Power Generation WECoMP Simulation (HP1)

5 Electrical supply and demand comparison

In this case study a period of 24 hours with no sailing period has been taken into account. what has been called the Harbour operational condition.

In this operative condition the wind generator and PV panels are able to produce enough electric power to satisfy the electric request. As shown in Fig.7, the RES power production exceeds the electric request in most of the periods of the day so that there is a surplus of energy that can be stored into onboard batteries

or into H2Boat Energy system, particularly in the middle of the day. Also using only the PV modules in a unwind day. in some hours of the day the solar production exceeds the request. Tab. 6 shows the total amount of energy available from renewable sources.

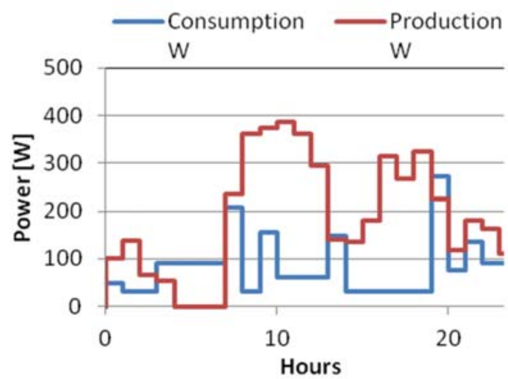

Figure 7: RES power production and electric request in Harbour condition

The previous Harbour condition features were repeated in the other considered operational conditions. The Renewable Generators exceed the electric needs of the boat producing electrical energy that would be conveniently stored exploiting the best available technology as it will be described in the following.

6 Innovative Energy Solutions State of the Art

An assessment of the available solution able to power an electric boat is given, with particular attention to the hydrogen technology solutions.

Electricity is an energy vector with (having) extremely good characteristics for what concern power production and flexibility of usage [12]. On the other side, electricity cannot be stored with the same easiness. actually the only system able to store big amount of energy by means of electrochemical reactions are the galvanic cells

Table 6: RES energy production

PRODUCTION HP 1	OPERATIONAL CONDITION				
Wh	NAVIGAZIONE 24h	RADA 24h	DAY CRUISE	CRUISE 24h	Average
PV	1496.4	1496.4	1279.0	1496.4	1442.1
WIND	0.0	3033.0	369.0	1671.0	1268.3
HYDRO	5195.0	0.0	1280.0	1405.0	1970.0
PV+WIND+HYDRO	6691.4	4529.4	2928.0	4572.4	4680.3

Table 7: Maritime fuel cell applications

#	Name	Typology	Yeat	Fuel cell	Power [kW]	Storage
1	Hydra	Boat	2000	AFC	5	Hydrides
2	Watertaxi	Boat	2003	PEMFC	4x1.5	NaBH4
3	Hydroxy 3000	Boat	2003	PEMFC	3	CH2
4	Zobotec	Boat	2005	PEMFC	0.8	CH2
5	Solgenia	Boat	2005	PEMFC	3x1.2	CH2
6	H2Yacht	Boat	2005	PEMFC	2x1.2	CH2
7	Xperiance	Boat	2006	PEMFC	1.2	CH2
8	Riviera 600	Boat	2009	PEMFC	4	CH2
9	Urashima	AUV	2003	PEMFC	4	Hydrides
10	Deep C	AUV	2004	PEMFC	-	Hydrides
11	Canal Boat	Canal Boat	2007	PEMFC	1	Hydrides
12	ZEMSHIP	Canal Boat	2006	PEMFC	48	CH2
13	NEMO H2	Canal Boat	2008	PEMFC	60-70	CH2
14	No 1 Yacht	Sailboat	2003	PEMFC	4x1.2	CH2
15	XV 1 Yacht	Sailboat	2006	PEMFC	10	Hydrides
16	Zero CO2	Sailboat	2010	PEMFC	25	CH2
17	Viking Lady	Support vessel	2009	MCFC	320	LNG
18	U212	Submarine	2002	PEMFC	120	Hydrides

[13]. The principle of galvanic cells is exploited in the batteries technology as well as in the fuel cell technology. The main difference between batteries and fuel cells lays on the chemical electrodes. The first uses solid metallic based electrodes that limit the amount of energy that can be stored and produced. The second instead. uses gaseous electrodes so that the cell could work virtually indefinitely until the gaseous are provided [14]. In Tab.6 [15] there is a short summary of present fuel cell marine applications. As can be seen from the table. the most used typology of fuel cell is the Proton Membrane Exchange (PEM) fuel cell, while the most common hydrogen storage systems are the Compressed Hydrogen (CH2) system for surface application while Hydride system are mainly used for underwater application as submarines and AUV. Many of the previous applications are prototypes. ZEMSHIP and NEMO H2 are two important and particular applications while the U212 represent the higher level available at the present time for this technology.

7 H2Boat

7.1 Introduction to H2Boat Solution

Sailboat up to 40 ft are usually equipped with a main propulsion engine directly connected to the propeller, a DC system coupled with a battery storage and an axis generator able to give energy both to the batteries and a limited AC system by means of an inverter. A scheme of the electrical system of a typical sailboat that considers also the presence of renewable sources is reported in Fig.8. The DC system is dimensioned considering the Energy balance while the AC system is considered as an auxiliary system and due to its elevate energy consumption it usually works in conjunction with the main engine.

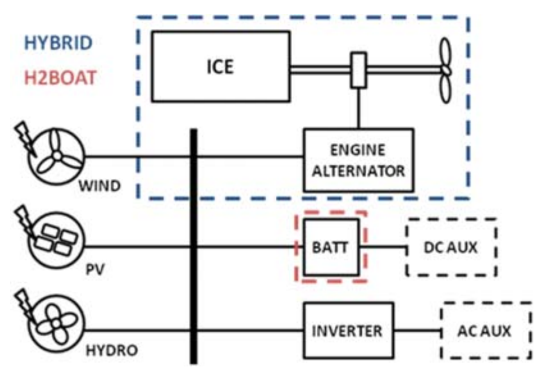

Figure 8: Electrical system of a typical sailboat

Since the battery is the heart of the DC system its performance is the key point for the improvement of the performance and operability of the whole boat. In the following the H2Boat concept aiming to improve the performance of micro power generation onboard and of electrical storage, is described. H2Boat solution is a new kind of hybrid boat whose target is to reduce emissions. improve energy flexibility and overcome batteries technology.

7.2 H2Boat Solution

H2Boat is an innovative system that is under study at the University of Genoa that proposes the use of hydrogen technology on sailboat. H2Boat is an energy pack composed of a PEM fuel cell, an electrolyser and a hydrides hydrogen storage. Fig.9 shows the components of the systems and their connections.

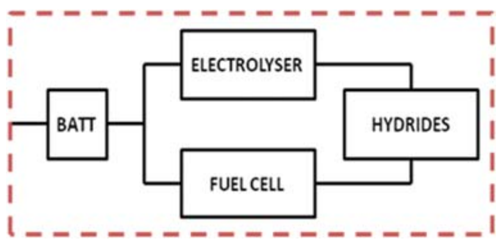

Figure 9: H2Boat components

H2Boat System is an energy pack that can store and produce energy independently whenever it is needed overcoming the present limitations of storage technologies (batteries) looking at their electrical features but also at their volume and weights.
To produce hydrogen the H2Boat system is provided with an electrolyser that transforms electrical energy into hydrogen. To store the energy, now in the gaseous form of hydrogen, a hydrides storage system is provided and finally, to transform the energy back into electricity a fuel cell is installed. By splitting the functions of the electrical storage system, inevitably both the volume and the weight increase in respect with a traditional battery, but since the fuel cell works as a fluxes battery, an increasing amount of energy storage means the installation of additional hydrides but no more fuel cells or electrolysers, in this way the ratio between energy stored and volume decreases as well as the ratio between stored energy and weight decreases making the H2Boat system competitive, as shown in Fig.10 and Fig.11.

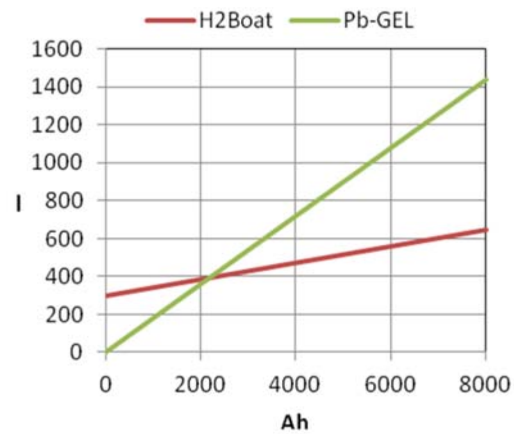

Figure 10: H2Boat vs Batteries volumes

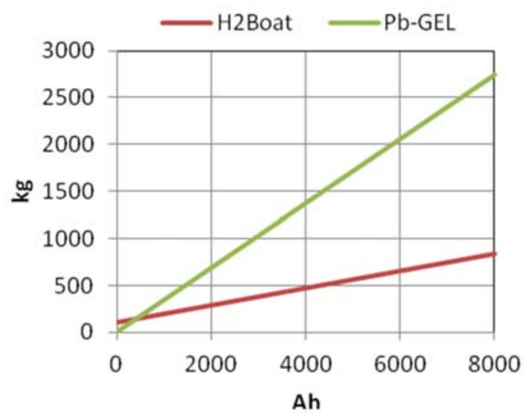

Figure 11: H2Boat vs Batteries weights

What makes the system bulky and heavy is the presence of two additional components over the storage system, represented by the hydrides, which are the fuel cell and the electrolyser. The dimensions of the first component are related to the maximum power required while the electrolyser dimensions are connected to the hydrogen mass flow speed rate to be produced. This two factors have to be evaluated carefully

Table 8: Maritime fuel cell applications

		H2Boat #1		
	Battery	Fuel Cell	Electrolyser	Hydrides
Voltage [V]	12	12-24	24	-
Capacity [Ah]	120	-	-	208*
Weight [kg]	41	75	50	19
Volume [l]	21.6	171	125	9.2
Specific Weight [Ah/kg]	1.76	-	-	10.95
Density [Ah/l]	3.33	-	-	22.61
(*) stechiometry fuel cell consumption				

Table 9: H2Boat components characteristics

		H2Boat #1		
	Battery	Fuel Cell	Electrolyser	Hydrides
Power [kW]	5400-9120	5	2.6	-
Dimension [mm]	513x189x223	560x500x610	0.5x0.5x0.5	478x77x236
Flow [Nl/h]	-	-	500	-

since their value will condition not only the electrical balance but also the structure of the boat energy system. The data that has been considered for the batteries and the fuelcell/electrolyser/hydride H2boat system are reported in Tab.8 and Tab.9 [18][19][20][21].
In Tab.10, it can be seen that the H2Boat system requires a fixed total volume of 296 l for a total weight of about 125 kg to which it must be added the volume and weight of the hydrides. From this assessment it is possible to evaluate in about 2000 Ah (24 kWh at 12 V) the minimum value of energy that the system should store in order to become competitive.
In order to improve the functionality of the fuel cell based system and to take advantage of the separate hydrogen storage system as well as to improve safety and to comply with the international maritime rules an innovative solution for the hydrides installation has also been considered. The concept is to move weight where it is needed and also to isolate the hydrogen storage in an intrinsic safety space installing the hydride storage inside the keel, so the H2Boat system results more light and less bulky on board improving the boat energy performance without taking away useful spaces nor adding additional weight onboard. In Tab.10 is reported a comparison between a battery system and a H2Boat with 30 kWh of energy storage underlining the saving of volume and weight.
For what concerns the keel, the hydride system specific weight is comparable with that of the typical material used at the present for this structural purpose, Tab.11 [22], but weight lighter so that an equivalent keel should be larger or made by composed materials. In order to obtain conservative results, one of the lighter hydrides available on the market has been considered. The hydrides weight range depends from the typology of the hydrides and the structure of the hydrides system (with or without the water heat exchanger) and it strictly connected to the flow rate, and varies from about 2000 to 15000 kg/m^3.

Table 10: 30 kWh System Comparison

		H2Boat #1		
30 kWh	Battery	Fuel Cell	Electrolyser	Hydrides
Total Weight [kg]	1423.61	125.0		228.4
Total Volume [l]	750.00	296.0		110.6
Utilization factor of 0.6 for the battery and 0.83 for the fuel cell				

Table 12: Extra commodities consumption

Component	Power	Utilization Factor	Average Energy
-	watt	Hour/day	Wh
Microwave	2000	0.1	200.0
Coffe machine	1200	0.2	240.0
Hot water boiler (10 l/day)	580	1.0	580.0
Water maker (150 l/day)	120	5.0	600.0
Electric stove	6000	0.2	1200.0
Air conditioning	1400	6.0	8400.0
Total	11300	-	11220.0

Table 11: Keel material specific weight

Lead	11340	[kg/m^3]
Tungsten	19250	[kg/m^3]
Cast Iron	7200	[kg/m^3]
Hydrides	2200	[kg/m^3]

7.3 H2Boat Sizing

In the paragraph 7.2 Tab.8, some important assumption have been done on the Fuel Cell power and on the electrolyser hydrogen flow rate that have been chosen respectively of 5 kW and 500 Nl/h, characterizing the system configuration called H2boat #1. This choice was done according to the electrical requirements listed in the following :

Fuel Cell power:

- Average power required for Auxiliary systems
- Propulsion power, depending on the required boat speed

Electrolyser hydrogen flow rate:

- Maximum available power from renewable source
- Time available to completely refill the hydrogen tanks

Hydride storage capacity:

- Average energy consumption
- Operational profile

Looking at the electrical power demand (tab.1) some typical sailboat comfort devices are not considered (Coffee machine, microwave, air conditioning…) whose daily use increases electrical consumptions. In Tab.11 [23][24] is reported a list of some common electrical comforts, all of which (except the water maker that can work with DC) works in AC, so requiring the usage of the energy consuming inverter.

From the values listed before, it can be gather that the energy consumption could increase up to 5 times, depending of what component is installed. The power requirements depends on the simultaneity of the active components, a factor that can also be controlled. Concerning the Fuel Cell sizing. the maximum operating power is established on the average value of the power requirements since FC systems operate in conjunction with a small battery required to supply energy during the power peaks. For this reason the pivot value that influence the FC maximum power is the propulsion requirement. more than the auxiliary systems. The indicative values of power required to move a 40 ft. sailboat at the speed of 5 and 7 knots are reported in Tab.13 [23].

Table 13: Propulsion power requirements

Speed [kts]	Power [W]
5	1200
7	2400

Considering the average power requirements of the auxiliary system between 400 and 1400 W and a small power surplus required to recharge the back-up battery of the FC system plus the propulsion power [1], it results a FC power in the range of 3.5 - 5 kW, Tab.14 shows the fuel cell considered.

Table 14: Fuel cell choice

Fuel Cell		
#	1	2
Power [kW]	5	3.5
Dimension [mm]	560x500x610	560x500x610
Weight [kg]	75	67

The sizing of the electrolyser depends mainly by two factors: the maximum power available from the renewable sources and the time needed to refill the hydrides storage. Two size of electrolyser have been evaluated as shown in Tab.15 [25][20]. The performances of the systems are different, in any case both are able to match the renewable source power peaks as shown in Tab.16 and Tab.17.
From the collected data it's possible to determine the time required to refill a hydride storage of 30 kWh by means of the electrolyser at full power reputedly connected to shore power, showed in Tab.18.

Table 18: Refilling time for a 30 kWh storage

Electrolyser	[days]
#1	1.4
#2	2.3

To conclude this preliminary sizing of a H2Boat system, two systems have been evaluated. System #1 that consider more powerful FC and higher rate electrolyser and System #2, both with the same hydride hydrogen storage of 30 kWh. The characteristic data of the systems are reported in Tab.19.

Table 15: Electrolyser performances

Electrolyser	Nl/h	kWh/h	Power [W]	kWh 24 h	η
#1	500	0.91	2600	21.9	0.35
#2	300	0.55	1300	13.1	0.42

Table 16: Matching renewable source and electrolyser #1

Renevable Source-elct #1	Average Power	Max Power	kWh/h	kWh 24 h	η
HP 1	389.0	719.0	0.14	3.3	0.35
HP 2	448.8	863.0	0.16	3.8	0.35

Table 17: Matching renewable source and electrolyser #2

Renevable Source-elct #2	Average Power	Max Power	kWh/h	kWh 24 h	η
HP 1	389.0	719	0.16	3.9	0.42
HP 2	448.8	863	0.19	4.5	0.42

Table 19: H2Boat systems

<table>
<tr><td rowspan="2">A</td><td colspan="3">H2Boat</td></tr>
<tr><td>Fuel Cell #1</td><td>Electrolyser #1</td><td>Hydrides</td></tr>
<tr><td>Power [kW]</td><td>5</td><td>2.6</td><td>-</td></tr>
<tr><td>Flow [Nl/h]</td><td>-</td><td>500</td><td>-</td></tr>
<tr><td>H2Boat Weight [kg]</td><td colspan="2">125</td><td>19 kg/2.47kWh</td></tr>
<tr><td>H2Boat Volume [l]</td><td colspan="2">296</td><td>9</td></tr>
<tr><td rowspan="2">B</td><td colspan="3">H2Boat</td></tr>
<tr><td>Fuel Cell #2</td><td>Electrolyser #2</td><td>Hydrides</td></tr>
<tr><td>Power [kW]</td><td>3.5</td><td>1.3</td><td>-</td></tr>
<tr><td>Flow [Nl/h]</td><td>-</td><td>300</td><td>-</td></tr>
<tr><td>H2Boat Weight [kg]</td><td colspan="2">102</td><td>19 kg/2.47kWh</td></tr>
<tr><td>H2Boat Volume [l]</td><td colspan="2">235</td><td>9</td></tr>
</table>

Table 20: Renewable energy production and surplus a)

	OPERATIONAL CONDITION				
Wh	NAVIGATION 24h	HARBOUR 24h	NAV DAY CRUISE 11h	NAV CRUISE 24h	AVERAGE
CONSUMPTION	2233.7	2036.7	908.7	2137.0	1829.0
Production HP 1	6691.4	4529.4	2928.0	4572.4	4680.3
Production HP 2	8187.8	6025.8	4207.0	6068.8	6122.4
Surplus HP1	4457.7	2492.7	2019.3	2435.4	2851.3
Surplus HP2	5954.1	3989.1	3298.3	3931.8	4293.3

Table 21: Renewable energy production and surplus b)

	Surplus HP 1	Surplus HP 2	Standard battery	Total HP 1	Total HP 2
Renewable Energy [Wh]	2851.3	4293.3	1829.0	4680.3	6122.4
Energy Storage [Ah] 12 V	238	358	152	390.0	510.2
Batteries capacity [Ah](*)	396	596	254	650.0	850.3
(*)Batteries utilization factor between 40% and 100%					

Table 22: Battery systems weight and volume

	Single Battery	Total HP 1	Total HP 2
Voltage [V]	12	12	12
Capacity [Ah]	120	650.0	850.3
Specific Weight [Ah/kg]	1.76	1.76	1.76
Density [Ah/l]	3.33	3.33	3.33
Weight [kg]	41	370.2	484.2
Volume [l]	21.6	195.0	255.1

8 Renewable energy exploitation

From the previous analysis made with WECoMP software, potentially, an average energy surplus of about 3 kWh/day is available from renewable sources through the usage of standard solar panels (200 Wp), wind (300 Wp) and hydro generators (500 Wp), in the case of the presence of only two solar panels (HP 1), while an average energy surplus of about 4,5 kWh is available if four solar panels are installed (HP2). Tab.20 reports a briefing of the assessment.

In order to exploit this energy, a battery based system should be sized in the way described in Tab.21.

The results in terms of weights and volume, two of the main factors that influence the efficiency of a maritime application, are listed in Tab.22.

In practice this solution it's never used if not for hybrid electrical boat who consider also an electrical propulsion that require energies up to 4,8 kWh/day and more in addition to the auxiliary requirements and the extra comfort, Tab.23.

In the period of time when no propulsion or extra comfort are active or only the comfort are active, the system is able to store about 3 kWh/day or 1.2 kWh/day of energy respectively. To deeply exploit the renewable sources though, the energy storage system should be able to store more energy.

Afterward a battery system able to store about 3 kWh, compatible with the operational profile of an electrical boat of 40 ft that nevertheless require the use of a generator or the engine alternator to restore the energy storage or to power the boat when more energy than the stored one is required, has approximately the same dimensions in terms of volume and weight of a H2Boat system that however is able to store 30 kWh.

Table 23: Energy Requirements (day)

Energy requirements (day)	Wh	Ah
Propulsion	4800	400
AUX Average consumptions	1726	144
AUX Average extras	1870	156
Total	8396	700

9 Conclusions

Hydrogen technology allows improved performance in terms of energy storage and generation; the fuel cells and related hydrogen energy system components market nowadays offers reliable performance and accessible costs products; innovative solutions to exploit this emerging technologies are ready to be explored and implemented in traditional applications overcoming the present limits especially in the field of electrical energy storage.

A sail-boat is a micro-reality able to explore the sea in complete autonomy, and today without compromising comfort nor safety issues during navigation and in harbour; in this paper a 40 ft. sail boat was chosen to explore the opportunity offered by an energy system made of renewable generators, an electrolyser, a hydride storage, and a fuel-cell to make the sail-boat completely autonomous respect the on-board electrical needs and maximizing the renewable energy contribution brought by the sun and the wind during sailing and harbour period.

After the definition of plausible operative conditions of the sail-boat, the electrical needs on-board result in the range of 900-2000 kWh/day while the production from renewable energy generation resulted in the range 3000 - 8000 kWh. Such a overmuch energy contribution from renewable source can be managed by the installation of an energy storage overcoming the limits of the present batteries pack, like the hydride hydrogen storage is. In this way without compromising weight and spaces on-board it is possible to obtain a storage capacity three times higher than the present standard installed by mean of chemical batteries, in addition to the opportunity of restore the energy reserve while using the boat by means of an electrolyser coupled to renewable energy generators.

The potential of the H2Boat energy system allows to define new standards in terms of electrical energy available on-board opening new developments for totally green sail-boats eventually equipped with electrical propulsion so that meet even the future restrictive environmental regulations that will be applied to pleasure boat sector.

Nomlencature

AC	Alternate Current
AFC	Alkaline Fuel Cell
AUV	Autonomous Underwater Vehicle
AUX	Auxiliary Systems
CH2	Compressed Hydrogen
DC	Direct Current
FC	Fuel Cell
HRES	Hybrid Renewable Energy System
ICE	Internal Combustion Engine
MCFC	Molten Carbonate Fuel Cell
NaBH4	Sodium Borohydride
PEM	Proton Exchange Membrane
PEMFC	Proton Exchange Membrane FC
RES	Renewable Energy System
WECoMP	Web-Based Economic Cogeneration Modular Program

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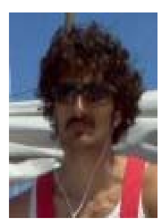

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Annex 1

	NAVIGATION 24h		HARBOUR 24h		DAY CRUISE 11h		CRUISE 24h	
Componenti	[h]	[A]	[h]	[A]	[h]	[A]	[h]	[A]
gps plotter	24	0.25			6	0.25	6	0.25
VHF	24	0.416667			6	0.416667	6	0.416667
Automatic Pilot	8	5					2	5
Anchor Windlass			1*	10.41667	1*	10.41667	1*	10.41667
Instrument and Measurements	24	0.125			6	0.125	6	0.125
Navigarion Lights	12	2.5			6	2.5	6	2.5
Anchor Light			24	1.25	4	1.25	18	1.25
Internal Lighting	12	5	12	5	1	5	12	5
Fridge**	24	1.388889	24	1.388889	11	1.388889	24	1.388889
Fresh Water Pump	3	8.333333	3	8.333333	1	8.333333	3	8.333333
Radio			3	2.5			3	2.5
TV/Computer			2	3.75			2	3.75
(*) 7.5 minuts of operation considered								
(**) 1/3 of maximum power over 21 hour/day and maximum power over 3 hour/day								

INNOVATIVE POWER SYSTEM FOR AUTONOMOUS UNDERWATER VEHICLE

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Abstract— *The present paper proposes a study for the integration of a hybrid power system composed by rechargeable batteries and fuel cells with chemical gas storages for an Autonomous Underwater Vehicle (AUV) or Unmanned Undersea Vehicles (UUV). AUVs and UUVs are vehicles that are primarily used to accomplish oceanographic research data collection and auxiliary offshore tasks. At the present time they are usually powered by lithium-ion secondary batteries, which have insufficient specific energy. In order to enhance the usage of these vehicles and to exploit their capabilities an increased endurance is required. Fuel Cell Energy Power Systems (FCEPS) have been identified as an effective means to achieve this endurance[1]. From literature it could be found that the present technology to power AUV is based on rechargeable batteries implemented with some form of battery management system. In order to improve the autonomy of the vehicles different technologies should be used. The state of the art is represented by the HUGIN AUV[2]. This vehicle is powered by a Alkaline Aluminium/Hydrogen peroxide semi-fuel cell. This paper will present an alternative power generation system based on a Proton Exchange Membrane (PEM) fuel cell fed by pure hydrogen and oxygen produced by a replaceable chemical storage for AUV. A technical sizing of the system has been done, supported by an analysis of the performance of the considered technologies. Standard AUV-UUV works on daily operational profile and thus have about 24h of autonomy. FCEPS for UUV requires particular characteristics of the vehicle to be installed and exploited. Starting from a statistical assessment of the existing UUVs for military and civil application an analysis of the most suitable dimensions, form and weight of the vehicle has been done together with an assessment of the requirements for different operative conditions in order to identify the most profitable target parameters for a future market development of this technology. The analysis of the application of an innovative hydrogen storage technology based on aluminium-water reaction is introduced for the first time. The study consider the performances of the system developed by the Technion Institute of Haifa (Israel), and present an evaluation of the theoretical achievable performance of the storage system and it's exploitation for particular matching with the Fuel Cell System (FCS). An assessment of the performance of the FCEPS, that consider the combination of FCS and storage system, has been done through the procedure proposed by Davis and More[3] considering the best oxygen storage system and the best FCS. This procedure has been developed for the application of FCEPS on UUVs and gives the methodology to calculate key parameters that permit the comparison between different systems. Moreover this method has been also used by other researchers and today it's available a wide database of systems performances available.*

Keywords—AUV; UUV; Hydrogen; Fuel Cell

NOMENCLATURE

AIP	Air Independent Power/Propulsion
AUV	Autonomous Underwater Vehicle
BOP	Balance Of Plant
ED	Energy Density
FC	Fuel Cell
FCEPS	Fuel Cell Energy/Power System
FCS	Fuel Cell System
HWV	Heavy Weight Vehicle
ITTC	International Towing Tank Conference
ISR	Intelligence, Surveillance and Reconnaissance
LWV	Light Weight Vehicle
MCM	Mine Countermeasures
ONR	Office of Naval Research
PD	Power Density
PEM	Polymer Electrolyte Membrane
RBEPS	Rechargeable Battery Energy/Power System
SE	Specific Energy
SP	Specific Power
SS	Storage System
UUV	Unmanned Underwater Vehicle

I. INTRODUCTION

AUV and UUV are used in both commercial and military field [1] and exist in a large number of configurations [2]. The development of a new project is very expensive, for this reason it is fundamental to assess the right typology of UUV and the right technologies to be used. For the latter, a new kind of SS has been found compliant with the requirements and will be presented. Among the many requirements that a new design should fulfil, the following data have been considered as the minimum threshold, Table 1.

TABLE 1. MINIMUM THRESHOLD

Autonomy	>24 h
Energy	>50 kWh

This study will compare the performances of a FCEPS with the innovative SS with the ones listed in Davies & Moore [3], that together with Mendez et al [2] represent the best comparative data collection of FCEPS for UUV. While Davies & Moore [3] consider a Large Displacement Mission Reconfigurable UUV of 60 inches of diameter (60''LD MRUUV) as reference platform, this study will present an assessment of the ideal size of a UUV with high energy requirement based on a market analysis.

A. General Requirements for UUV

When the concept of a UUV is designed, a complex work of matching between the operational requirements and the technical specifications should be done. The technology areas that are usually considered can be resumed from Martz [4] and are: Sensors, Communications, Navigations, Energy, Data signal processing, Autonomy, Structure, Vehicle control, Host interface, Logistic support. Each of these areas have influences on the others and on the final technical specification of the vessel. For this reason the ONR gave a number of recommendations for the development of UUVs among which standards. In fact, significant efficiencies can be realized by focusing the development towards standard vehicle sizes. SECNAV [1] gives the standards, shown in Table 2.

Although commercial applications are growing especially in the oil and gas industry [5] but not only, statistical data of the UUV market shows that the largest part of the UUV are produced for military applications [6]. For these reasons ONR standard size vehicles and mainly military applications have been considered for this preliminary assessment.

TABLE 2. UUV CLASSES

Class	Diameter cm	Displacement kg	Endurance h
Man-Portable	7.6-22.8	<45	10-20
LWV	32.4	~226	10-40
HWV	53.4	<1360	20-80
Large	>91.72	~9000	100->400

From [1] it's possible to extract the evaluation of the TRL for UUV subsystems versus the Sub-Pillar functions defined by the ONR, where it results that the key issue of the vehicle is autonomy. In brief it could be said that, while power considerations usually dominate the design of UUVs, energy is the most limiting resource [7]. To exploit the operational benefits of UUVs, high energy density power sources are needed. One of the area that will provide most benefit to the subject is represented by battery and fuel cell technologies. If the typical performance figures of electrochemical power sources for a generic UUV are considered [8], listed in Table 3, it is possible to figure out that the most promising technology are indeed Hydrogen-Oxygen fuel cells and Lithium batteries. From the assessment it could be concluded that in order to increase the energy storage, fuel cell technology is the most promising solution and actually the HUGIN AUV, equipped with an alkaline aluminium hydrogen peroxide semi-fuel cell described by [8] and [9] represent the highest level of FCEPS for a UUV. To exploit the potential benefits of FCEPSs, HWV and Large vehicles should be considered [1]. Thresholds and objectives for large displacement military vehicles can be found in [11], here resumed in Table 4.

TABLE 4. NAVY LD MLUUV FCEPS THRESHOLD AND OBJECTIVE REQUIREMENT

FCEPS threshold	**Energy** 1725 kWh	**FCEPS objective**	**Energy** 11500 kWh
Volume 5663 l	**Energy Density** 0.305 kWh/l	**Volume** 3681 l	**Energy Density** 3.124 kWh/l
Mass 7575 kg	**Specific Energy** 0.228 kWh/kg	**Mass** 4082 kg	**Specific Energy** 2.817 kWh/kg

B. General Requirements for UUV's FCEPS

Hydrogen-Oxygen fuel cell technology has been found as the unique technology able to fulfil the future energy requirements while HWV and Large size vehicle has been found as the ideal vehicle target size [8]. Considering FCEPS for UUVs, Davies & Moore [3] gives a list of general requirements for FCEPS design and propose a design methodology. The report consider the 60''LD MRUUV as the

TABLE 3. TYPICAL PERFORMANCE FIGURES OF ELECTROCHEMICAL POWER SOURCES FOR UUVS

Technology	Type	ED Wh/dm^3	Endurance h	Safety	Cost	Logistic/ Maintenance
Lead acid	Rechargeable	10-20	4-8	H	L	L
Alkaline	Primary	10-30	4-12	H	L/H	L
Lithium Polymer	Rechargeable	50-75	20-30	M	M	L
Aluminium-Oxygen	Semi fuel cell	80-90	32-36	M	M	H
Hydrogen-Oxygen	Fuel cell	100+	40+	L	M	H
Lithium	Primary	100-150	40-60	L	H	L
Low (L); Medium (M); High (H)						

nominal application for the FCEPS technology assessment and as a conclusion states that the best FCEPS is composed by the combination of the 60% lithium hydride slurry system (Safe Hydrogen, LLC) and the CAN 33 chlorate candles (Molecular Products) for a SE and a ED of 0.44 kWh/kg and 0.48 kWh/l respectively. Among the requirements that should be considered, the following are considered the most important: Mass, Volume, Energy, Power, Buoyancy, Form, Deepness, Modularity, Operation. The last one consist in fuelling procedure, startup and shutdown time, mother vessel equipment, crew training. These aspects are the reason why the semi fuel-cell are not used anymore onboard the HUGIN class AUV.

II. *PLATFORM ASSESSMENT*

The following study will present a different nominal platform for the FCEPS chosen considering technical specifications and market trends.

A. *Statistical Analysis*

In order to identify the proper UUV's dimensions able to fulfil the requirements of Table 1, an assessment of 112 vehicles, 48 platform from 15 companies has been done. About 55 more UUV have been considered from research centres, Universities and other laboratories. Data has been collected from AUVAC [6]. Considering that military applications of UUV represents the largest part of the market, it has been chosen to focus the technical specifics mainly on them. SECNAV [1] identify 9 different mission profiles that have been used to classify the vehicles: Intelligence, Surveillance and Reconnaissance (ISR); Mine Countermeasures (MCM); Anti-Submarine Warfare (ASW); Inspection/Identification; Oceanography; Communications/ Navigation Network Node (CN3); Payload Delivery; Information Operations (IO); Time Critical Strike (TCS). The largest part of the UUV comply with the first two applications, for this reason the analysis has been focused on them. From the statistical data important choices as Form, Mass and Deepness can be evaluated. Figure 1 shows the major results of the assessment.

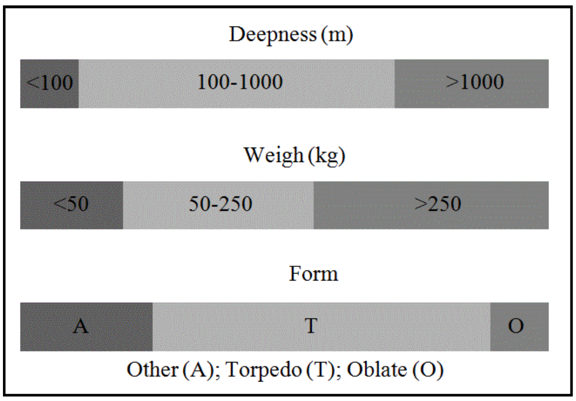

FIGURE 1. STATISTICAL ANALYSIS

Taking into account the statistical data acquired from [6], considering ISR and MCM applications together with the requirements of Table 1, two vehicles has been chosen as reference design, the Kongsberg Hugin 1000 and the Saab AUV62-MR.

B. *Reference Platform*

One of the results of the statistical data assessment has been to consider a UUV with a Torpedo form able to afford the pressure of at least 1000 m of deepness. The reference mass has been considered of 1000 kg considering the two reference design cited before. In order to maintain a density 10% higher of standard salt water (1.026 kg/l at 15 °C ITTC), the mass can vary from slightly less that 1000 kg to about 1300 kg depending on the volume of the vehicle. In order to consider the most flexible platform, an external diameter of 0.53 m has been considered to take into account the possibility to release the UUV from submarines. For what concern the length of the vehicle, it has been considered that it could be designed with a modular concept, in order to maximize the flexibility of the UUV. This means that the final length could vary between about 4.5 to 6 m. Figure 2 shows the statistical data of MCM UUVs with respect to form, mass, length and operative deepness [6]. It could be seen that the target vehicle is between two or three quite recognizable class of vehicles that can be well represented by the reference vehicles that has been chosen. Moreover, it has been checked that the target vehicle dimensions were compatible with the ones of ISR UUV as shown in Figure 3 that represents the statistical data of ISR UUVs with respect to form, mass, length and operative deepness [6].

Thanks to the statistical assessment it has been possible to evaluate the main dimensions of what can be considered as one of the most common UUV with high energy requirements available on the market, in Table 5.

TABLE 5. GENERAL UUV MAIN DIMENSIONS

Length	5	m
Diameter	0.53	m
Mass	1000	kg
Form	Torpedo	-
Deepness	>1000	m

C. *Performances*

To design the FCEPS for the target vehicle, an evaluation of the power and energy requirements should be done. For a specific design, an evaluation of the required power to move the vehicle can be done using the equation proposed by [7]. The equation gives the relationship between power, range and speed. A slightly different equation is given by [12]. For this study, an equation has been derived from the previous ones, Eq. (1), and has been validated on the available data of the HUGIN 1000 [10].

$$R = (E * 3600)/\left(C_t * 0.5 * \rho * S * u^2 * \frac{1}{\eta} + \frac{P_H}{u}\right) \quad (1)$$

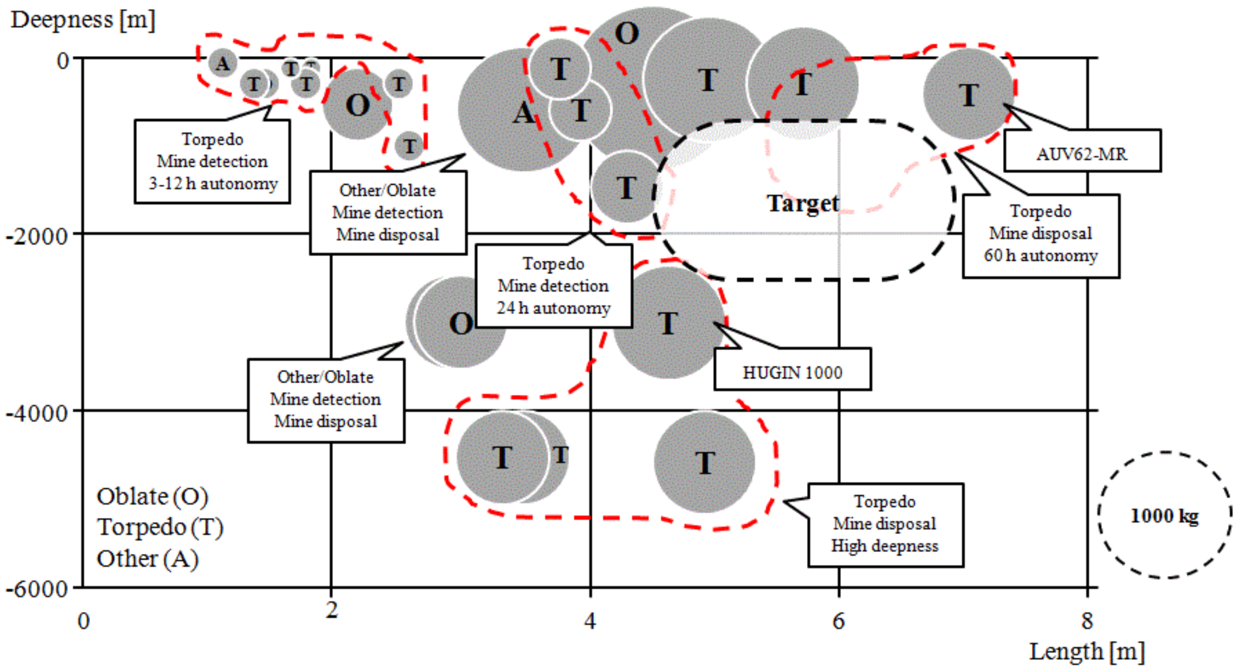

FIGURE 2. TARGET VERSUS MCM UUVS DATA

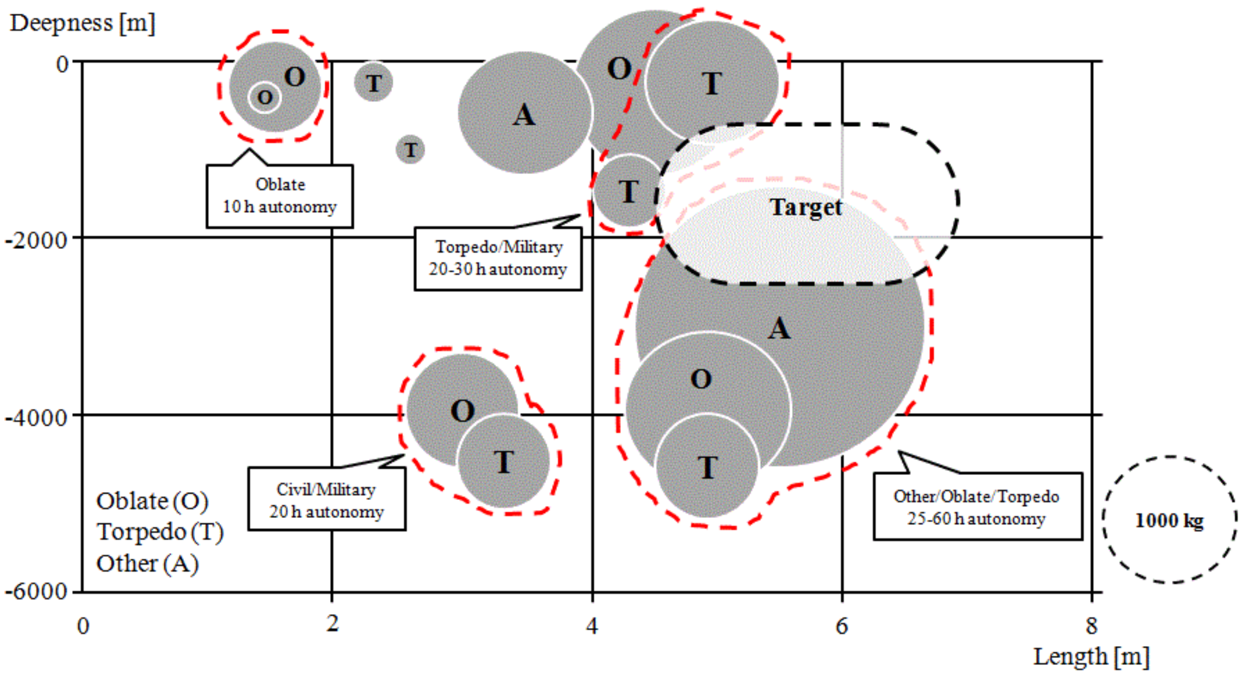

FIGURE 3. TARGET VERSUS ISR UUVS DATA

Where:

R = range [m]
E = 50 [kWh] energy stored
C_t = 0.01 drag coefficient
ρ = 1025 [kg/m^3]
u = speed [m/s]
η = 0.85 propulsion efficiency
P_H = 150 [W]Hotel power

On the base of Eq. (1) it's possible to evaluate the power consumption of the reference UUV at a speed of 3.8/4.0 knots. This speed is the minimum required in order to have a good control of the vehicle using only the rudder, otherwise external fins are required resulting in a higher system complication. As results, a continuative power of about 500 W is required to move the UUV at 4 knots during operation that could be MCM or ISR. When the UUV is moving towards the operation site though, a higher speed is required of about 7

TABLE 6. HYPOTHETICAL OPERATIONAL PROFILE

Profile	Time h	Range km	Speed kts	Power W	Energy Wh
Transfer	10	130	7	2200	22000
Operation	50	370	4	540	27000

knots, that results in a power requirement of 2000/2500 W. Finally a simple hypothetical operational profile has been constructed: 10 hours transfer, 50 h operation.

On the base of this hypothesis it's possible to evaluate the required power of the FCS. The results are listed in Table 6. The total energy consumption is of about 50 kWh, as required from the threshold in Table 1. It is proved that the considered target energy match a general operational profile for the considered target UUV (military for MCM and ISR mission).

III. FCEPS

From the collected data it is now possible to evaluate the volume dedicated to the FCEPS of the most general UUV able to install a FCS. Taking into account a 50 kWh of energy storage, considering the threshold energy density requirements of Table 4, the resulting FCEPS volume and mass should be V=164 l and M=220 kg. If the density of the system is calculated with these values, it results that the system has a 1.3 kg/l density, much higher than water. In order to consider a more valuable threshold, the mass value is evaluated from the threshold volume of 164 l considering a density for the system equal to 1.13 kg/l (10% higher than salt water). The result is a threshold mass of 185 kg. If an internal diameter of 0.50 m is considered, the required vehicle length to be dedicated to the FCEPS is 0.84 m. Table 7 resumes the value of volume and mass dedicated to the FCEPS of the most common medium/large size UUV referred to the equivalent energy threshold value set by the ONR and resumed in Table 4.

TABLE 7. GENERAL UUV FCEPS ENERGY THRESHOLD

FCEPS threshold	**Energy** 50 kWh
Volume 164 l	**Energy Density** 0.305 kWh/l
Mass 185 kg	**Specific Energy** 0.270 kWh/kg

The FCEPS design concept presented in this report uses a holistic approach introduced by Davies & Moore [3] in combining alternative hydrogen and oxygen storage, and fuel cell system options to provide the highest specific energy (SE) and energy density (ED) within the UUV constraints, including the FCEPS mass, volume, and required power.

The Davies & Moore [3] report conclusion was the best combination of FCS and oxygen and hydrogen SS for the 60'' LD MRUUV. This study will compare the new hydrogen SS with the one considered by Davis and will assess an evaluation of the best combination of FCS and SS for the general UUV FCEPS described before.

A. FCS

Taking into account the FCS comparison presented in Davies & Moore [3], the rapid conclusion is that the most feasible FCS for marine application is the Siemens BZM 34. It should be considered that BZM 34 and BMZ120 are composed by the stack together with the BOP and that they have been installed in at least 16 submarine applications. The performance of the BZM 34 FSS is reported in Table 8 [13].

TABLE 8. SIEMENS BZM34 SPECIFICATIONS

Power (nominal)	34 kW
Volume	334 l
Mass	650 kg
Dimensions	47x47x143 cm
Active Area	1180 cm^2
Number of cells	72
Cell thickness	2.2 mm
SP	0.052 kW/kg
ED	0.102 kW/l

On the base of this data it has been possible to evaluate the specific power (SP) and the power density (PD) of the FCS. Moreover considering the ratio between the FCS area and the active area and the ratio between the total cells length and the FCS length, it has been possible to evaluate the dimension of a similar 1000 W nominal power FCS (at 0.6 A/cm^2), considering 100 cm^2 of active area and 24 cells. In the end, it should be considered that BZM technology is quite old, and that today it's possible to reach the same cell voltage (0.78-0.72 V) with current density higher than 0.3-0.6 A/cm^2.

B. SS 02

There are several classifications of oxygen storage, including compressed, liquid, and chemical. Davies & Moore [3] concluded that chlorate candles are among the best oxygen storage solution, indeed the Molecular Products CAN 33 has been found as the best choice. The chlorate candle is a mixture of sodium chlorate, iron, a small amount of barium peroxide, together with a fibrous binding material. The basic process in burning the "candle" is the thermal decomposition of the chlorate, Eq. (2):

$$NaClO_3(s) + Fe(s) \rightarrow NaCl(s) + 2O_2(g) + Fe(x)O(y)(s) \quad (2)$$

Each candle burns at about 200°C for 45-60 minutes, and produces approximately 3200 Nl of O2 at 1,047 bar(a). The smoke and salt also produced must be separated by filtration. The stored candles represent a significant fire hazard since they are self-sustaining in oxygen. The most complicated factor of the technology comes from the careful manipulation of the iron and sodium chlorate concentrations in order to control the rate of the reaction and the volumes produced.

Once the reaction has been started it will instantaneously produce oxygen that is at ambient temperature by the time it reaches the dispensing point. These characteristics make the chlorate candles the most promising oxygen storage system for a UUV. Davies & Moore [3] listed 5 different chlorate candles performance that have been taken into account during the analysis.

C. *SS H2*

The Davies & Moore [3] assessment considers four types of hydrogen storage: compressed, liquid, metal hydride, and chemical hydride. Other hydrogen storage approaches have been excluded. The present study propose the application of the storage based on aluminium-water reaction. For the purpose will be considered the system developed by Technion (Israel Institute of Technology), better described in [14]. The aluminium-water reaction considered is:

$$Al + 3H_2O \rightarrow Al(OH)_3 + \frac{3}{2}H_2 \quad (3)$$

The novel thermo-chemical process of aluminium activation developed at Technion, makes the aluminium oxide layer non-protective and allows a spontaneous and sustained chemical reaction between aluminium and water which produces hydrogen. All types of water can be used. [15] proved high reaction rate with high efficiencies (>90%). The stoichiometric reaction of Eq. (3) yields theoretically 11% hydrogen mass compared to the aluminium mass (equivalent to over 1.2 l of hydrogen per gram of aluminium), making the concept very efficient for hydrogen storage. Table 9 shows the characteristic energy density of the aluminium powder developed by Technion:

TABLE 9. TECHNION POWDER CHARACTERISTICS

Volume density	0.13	kg H2/l*
Specific weight	0.11	kg H2/kg*
Energy Density	5.12	kWh/l*
Specific Energy	4.33	kWh/kg*

As can be seen from Eq. (3), the stoichiometric molar ratio between water and aluminium is 3 (corresponding to a mass ratio of 2). While for open vessel higher ratio can be required, for closed vessel the stoichiometric value can be sufficient (Technion data). If aluminium properties are considered for the stoichiometric reaction, taking into account the respective molar weight of aluminium, water, aluminium hydroxide and hydrogen, the theoretical performance of the system are the ones given in Table 10.

TABLE 10. ALUMINIUM HYDROGEN SS PERFORMANCES (INITIAL)

H2O 5,4 l	Al 1 l	64	cm^3
		81	g
		46,9	gH2/l
		37,0	gH2/kg

(*) referred to the Aluminium powder weight and volume (Technion)

Next to the table it is presented an indicative scheme of the volume occupied by the reactants before the reaction take place. In this case, all the required water is supposed to be stored in the system. Table 11 shows the energy performance and the scheme of the occupied volume at the end of the reaction.

TABLE 11. ALUMINIUM HYDROGEN SS PERFORMANCES (FINAL)

Free 3,2 l	Al(OH)3 3,2 l	ED	
		1,8	kWh/l
		SE	
		1,5	kWh/kg

Moreover, the water produced by the FCS since it is not used, must be stored in order to conserve the mass of the UUV requiring more space and penalizing the final energy density. As explained from Davies & Moore [3], when the FCEPS energy density is evaluated, it's important to consider the water generated by the fuel cell that is of about 8.9 kg water for each kg of hydrogen consumed. Since water is required for the hydrogen SS, the water produced by the FCS can be recirculated. In this case a weight ratio of 1:1 between aluminium and water can be considered (of storage). Table 12 and Table 13 shows the performance of the aluminium system before and after the reaction occurred in the case of water recirculated from the FCS.

TABLE 12. ALUMINIUM HYDROGEN SS PERFORMANCES WITH WATER RECIRCULATION (INITIAL)

Spare volume 2,7 l	H2O 2,7 l	Al 1 l	37	cm^3
			54	g
			81,1	gH2/l
			55,6	gH2/kg

TABLE 13. ALUMINIUM HYDROGEN SS PERFORMANCES WITH WATER RECIRCULATION (FINAL)

Spare volume 2,7 l	Free 0,5 l	Al(OH)3 3,2 l	ED	
			3,2	kWh/l
			SE	
			2,2	kWh/kg

Taking into account the FCS stoichiometric water production, it results that the produced water is equal to half the aluminium SS required water, for this reason the same amount of volume can be spared. The density of Technion powder is 1.18 kg/l, lower than aluminium density equal to 2.7 kg/l. Also if the powder density is lower, the same water ratio has been considered in the final evaluation of the Technion SS performance that are given in Table 14 and Table 15 for the initial and finial condition respectively.

TABLE 14. ALUMINIUM POWDER SS PERFORMANCES WITH WATER RECIRCULATION (INITIAL)

Spare volume 1,4 l	H2O 2,7 l	Al 2,3 l	49,9	cm^3
			54	g
			60,1	gH2/l
			55,6	gH2/kg

TABLE 15. ALUMINIUM POWDER SS PERFORMANCES WITH WATER RECIRCULATION (INITIAL)

Spare volume	Free	Al(OH)3	ED	
1,4 l	1,8 l	3,2 l	2,37	kWh/l
			SE	
			2,19	kWh/kg

In the end, considering Technion aluminium powder data, stoichiometric water requirements and FCS water recirculation, it is possible to resume the performance of the aluminium SS in Table 16.

TABLE 16. TECHNION HYDROGEN SS CHARACTERISTICS

Energy Density	2,37	kWh/l
Specific Energy	2,19	kWh/kg
Density	1.08	Kg/l

If these numbers are compared to the best hydrogen storage solution chosen by Davies & Moore [3], equal to 1.95 kWh/l and 3.36 kWh/kg, the aluminium SS have similar performances. It is not clear if the 60% lithium hydride slurry system (Safe Hydrogen, LLC) take into account also the water content, but the simpler system configuration of the aluminium SS can justify its use. Also, the hydrogen storage system performances have to be considered in combination to the rest of the system as shown after.

D. FCEPS

When the total performance of the hydrogen and oxygen SS are considered together with the performance of the FCS in terms of energy density (kWh/l) and specific energy (kWh/kg), the performance of the FCEPS is evaluated. This parameter results more significant than the previous ones because the lightest component can compensate the heaviest thus resulting in a optimum matching. If the aluminium SS is simply substitute to the 60% lithium hydride slurry system, it results that the FCEPS performance is lower, Table 17.

TABLE 17. LITHIUM SLURRY VS ALUMINIUM POWDER FCEPS PERFORMANCE

FCEPS	Lithium slurry	Aluminium powder
Energy Density kWh/l	0.48	0.45
Specific Energy kWh/kg	0.44	0.40

If different oxygen storage system are considered it is possible to rich higher performance depending on the density of the considered system. It is believed that chlorate candles are the best solution for oxygen SS, for this reason it has been chosen to consider the ideal sodium chlorate candle as comparison. Table 18 shows the achievable performance of the FCEPS if aluminium hydrogen SS is considered in combination to the ideal sodium chlorate candle.

TABLE 18. ALUMINIUM POWDER AND IDEAL CHLORATE BASED FCEPS

Energy Density kWh/l	0.52
Specific Energy kWh/kg	0.47

E. FCEPS FOR THE GENERAL UUV

It is now possible to evaluate the weight and volume of the FCEPS for the general UUV. Starting from the FCS, from the consideration made in chapter 3.1, the main dimensions of a FCS have been evaluated, Table 19.

TABLE 19. FCS FOR GENERAL UUV

Length cm	Area cm^2	Weight kg	Volume l
47.7	147.2	17.9	8.9

These values are comparable to the ones of other commercial fuel cell systems. The main result of the sizing is that it is been proved that a FCS able to generate 500-1000 W can be installed inside the space dedicated to the FCEPS (0.84 m length, 0.50 m diameter).

Considering the aluminium hydrogen SS and the ideal chlorate candle oxygen SS, the system performance achievable using all the remaining space and volume is of about 99 kWh (considering the FCS efficiency). A more realistic system is composed by an hybrid configuration that consider both fuel cell and lithium batteries. For this reason, if the hydrogen and oxygen SSs are limited to 50 kWh, the remaining space able to store a lithium battery is of 95 l, for 88 kg. For this evaluation it has been considered a Li-Fe-PO4 battery with 0.130 kWh/kg and 0,09 kWh/l. The results of the configurations are reported in Table 20.

IV. CONCLUSION

In conclusion two main parameters have been evaluated through this study. At first an evaluation of the most common UUV main dimensions has been done in order to consider the most used platform constrains where a FCEPS can be installed. The purpose of the study then, was to evaluate the performance of a new hydrogen storage system, that have been done in comparison to other investigated SS through a methodology based on the FCEPS density. The results show that generally the solid SS for hydrogen and oxygen are the best solutions and that the aluminium based hydrogen storage system is one of the most promising technologies. More

TABLE 20. HYBRID FCEPS FOR GENERAL UUV

System	FCEPS kWh	Lithium Battery kWh	ED kWh/l	SE kWh/kg
Only FCS	99	0	0.603	0.535
Hybrid FCS and Battery	50	8,3	0.356	0.315

deeper study should be conducted, some of them consider the water aluminium ratio in closed vessel, the proper oxygen storage system to combine, strategy of cartridge usage.

Acknowledgment

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Smart Port

exploiting renewable energy and storage potential of moored boats

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Abstract*— This paper presents a statistical and techno-economic feasibility study for the exploitation of renewable energy generators and energy storage devices typically installed onboard pleasure boats to transform harbors and ports in energy districts able to exchange energy with the grid. In Europe about 48 million citizens regularly participate in recreational marine activities (36 million of whom are boaters), as well as countless numbers of tourists. Over 6 million boats are kept in European waters while 4,500 marinas provide 1.75 million berths both inland and in coastal areas [1]. Thanks to the proposed Smart Port concept, this scenario could be considered as an energy resource to improve renewable energy penetration and enlarge European grid storage capacity with negligible investments by exploiting existing facilities. Starting from statistics assessment of ports and boats present on the Mediterranean Shore [2] (particularly in Liguria region) and considering data related to the Italian national electric market (daily spread between minimum and maximum price of electricity, daily renewable energy production and their impact on the price [3]), different scenarios are analyzed according to different kind of generators (photovoltaics, wind) and storage technologies [4] (batteries, hydrogen) commonly used in the nautical sector in order to study the most profitable solutions. A case study in Italy is presented and the expected impacts in terms of yearly renewable deliverable energy, storage capacity, CO_2 emission savings and money savings for boat owners and port managers is shown. This framework is analyzed at the present conditions and looking throughout future scenario that will include an increase of the number of electrical boats, a variable price of electricity and a decreasing price of batteries and hydrogen equipments as storage technologies. Considering the number of boats actually moored in the Italian marinas and equipped with renewable generators, relevant installation capital costs could be saved while the structural improvements that should be made to the ports are limited to the electrical connections and the smart control systems transforming it in an energy district able to interact with the electrical market through the national grid as a renewable generator or an energy buffer useful to the grid balance. The first required investment for the port will be the installation of bidirectional POD (point of delivery) and energy-meters, in order to make boats able to exchange energy with the grid while they are moored. It is important to underline that smart controls have to be investigated in order to guarantee a relevant state of charge of boats batteries. Suitable Business models enabling the exploitation of this new concept are shown. These models take into account the compensation rules to refund boat owners and other stakeholders, allowing sufficient profit margin to ports which would become actors in the energy market, interacting with the national grid as a RES producer, consumers and an electrical storages.

Keywords—Hydrogen, Ports, Energy storage

I. INTRODUCTION

There is a growing need to increase the usage of renewable energy sources in the energy system and the power generation mix. Addressing the issues related to the intermittency and unpredictability of these renewable sources poses important technical and economical challenges particularly when integrated on a large scale. Approaches to overcoming these challenges include: improved prediction of renewable production, back-up capacity, expansion of electricity grids (e.g. transport), demand-side management (e.g. smart meters, smart grid), and energy storage. Energy storage technologies provide attractive and promising solutions for energy management, bridging power management, power quality and reliability. However, although regulators and policy makers acknowledge the need to address these challenges energy storage solutions are not yet seen as a high priority. This aspect has an important impact on the results of the study that is presented.

II. ONBOARD RES AND STORAGES

Today Renewable Energy Source (RES) onboard boat generators are a typical equipment for small and medium boats (Length minor than24 m), particularly for sailboats, that represent also the reference for the study . Nevertheless There is no statistical data available about energy generators typically installed on boat and its evaluation is difficult. It is possible though to determine a sample boat with good approximation.

A. RES

to common sailboats moored in Italian harbors, The sample boat considered in this research is supposed to be equipped with three photovoltaic (PV) modules (100Wp for each module) and a wind generator (300 Wp). To simulate the performances of these generators three products available on the market are considered. Moreover a hydrogen fuel cell with a 3 kWp has been considered as part of an innovative power system. PV modules are considered to be able to produce 438 kWh/year while a production of 876 kWh/year is considered for wind turbine.

B. Energy Storage

Batteries are a common equipment for boats and today lead-acid is the most common technology. In this research only deep cycle batteries are considered in order to maximize the storage capacity and potential of the batteries and lead-acid and Li-On storage were taken into account. Each sailboat is considered to have at least 200 Ah of batteries capacity with a 12 V circuit tension corresponding to 2.4 kWh of energy storage capabilities. Lead acid batteries are supposed to have a 70% Deep of Discharge (DOD), while for Lithium ion batteries a 80% DOD is considered. Moreover an innovative hydrogen based power to gas system has been considered with a 40 kWh energy capacity and 2000 life cycle.

III. PORTS ASSESSMENT

In Italy there are 103500 registered boats[5]. Italian market is the second European market counting 1.4 yachting boat per 100 inhabitants in Italy, France counts 2.2 [6]. Among them, 99.7% have a Length minor than 24 m, while 24.6% are the sailboat registered in the Maritime Office, 81% of which are in the segment of 10 m<L<24 m, for a total number of about 19600 saiboat[5].

Italian infrastructure are able to moor about 147800 boats, where particularly Liguria region has 24200 moorings in its ports. 98000 Docks are dedicated to small size boats (L<10 m) while 46600 moorings are dedicated to medium size boats (10 m<L<24 m).

Looking at the electric connection of the moorings, an average of 87.9% can offer an electric connection to the shore[5] so that 31300 sailboats could be easily become an active actor on the electrical network, both as consumer, as producer and as energy storage system thanks to power production and storage equipment already installed on the boats.

It has been estimated that there are 75.2 MWh of energy capacity from battery storage are already available together with 9.4 MWp of installed photovoltaic power and the same quantity of wind power. In the following a case study is presented:

Liguria is the Italian region that presents the higher number docks as well as the higher number of registered boats in Italy. It has 71 harbors along its coast [7] that moor an average of 5250 sailboats with electric connection. Considering an average of 75 sailboat connected, it has been estimated that for a large port a total number of 200 connected sailboats is available. The simulation considered the energy and power exploitable from this sample port, 480 kWh and 60 kWp of photovoltaic power and 60 kWp of wind power. An evaluation of the sample harbor electric consumption has been done together with an evaluation of the energy supplied to the boats when they're moored in port in the summer, when they consume more than what they produce.

IV. ANALISYS

In order to analyze the potential savings and benefit from a smart energy management of a mean touristic harbor, mooring 200 boats electrical connected to the grid to recharge the batteries.

The zero hypothesis is the boat as pure user, which consumes the electricity provided by the port within the mooring services. The single boat yearly consumption was estimated to be 360 KWh/year, absorbed during a three months span (i.e. the summer season). The estimated yearly cost is about 125 euro per year.

Strategy A

This strategy suggests the use of the renewable energy source generators all years long in order to cover the boat energetic demand and selling energy to the grid. The electricity prices from RES were conservatively fixed as 100 eur/MWh for the PV, deduced by the Italian "quinto Conto Energia", and equal to 176 eur/MWh for the wind generator production as defined for the small offshore generators.

Capital costs were estimated basing on top marine commercial devices and divided for the system lifespan. The production was calibrated to the annual production values expected for climatic condition in a north Italian region, and reduced with respect to the non-optimized installation typical of the on boat systems. The saving per year is equal to ca 30 euro per boat. This make the solution viable.

Strategy B

This strategy takes into account the use of the chemical storage already installed on board (e.g. lead-acid deep cycle Batteries, Li-ion Batteries, and innovative Hydrogen storage). Performance and costs were deduced from commercial devices data sheet for the batteries and from previous calculation [4] for the hydrogen storage and are summarized in tab. 1.

Tab. 1 Comparison between chemical storage technologies

Parameter		Lead Acid	Li-ion	H2Boat
Nominal Capacity	kWh	2.4	5	40
DOD	%	80	80	95
number of Cycles	#	730	4000	2000
Cost/nominal capacity	eur/kWh	75	1700	750
total cost	eur	180	8500	30000
total energy	MWh	1.4	16.0	76.0
cost/ total energy	eur/MWh	€ 128.4	€ 531.3	€ 394.7

In particular, last row represents the cost of the storage of a MWh, taking into account also the life span of the different technologies. This value, represents also the minimum spread in electricity market price that makes profitable the use of that technology for electricity market trading.

Figure. 1 shows the daily spread frequency for the Italian market for the years 2012, 2013 and 2014. The daily market spread was calculated as the difference between the maximum and the minimum of the electrical market price, that for the Italian market is called PUN (acronym for Unique National Prize). This spread represents the highest gain achievable on the electricity market by the means of an electrical storage within a day with a charge/discharge time of an hour. It can be seen that the spread distribution over the past three years moved to lower values that means that the value of energy storage is lower than in the past. Moreover comparing the distribution with the minimum spread that ensure a gain for the chemical storage, last row of the previous table, it can be seen that this kind of activity can be hardly re-paid by the pure trade on electricity market, and just for the lead-acid batteries there are some opportunities when the spread is higher than 130 eur/MWh.

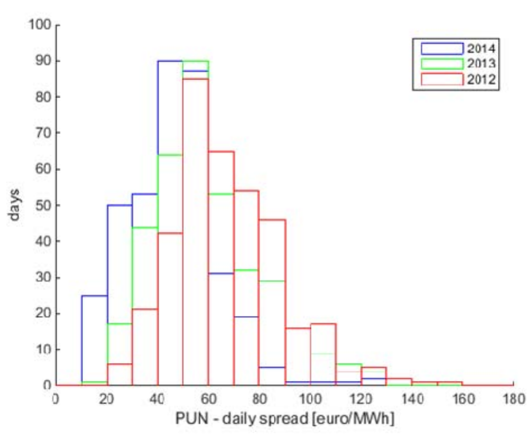

Fig.1 daily spread frequency over the past three years

V. Presents and future scenario

A. Present

The present Energy market does not permit the exploitation of port and boats infrastructure to make profit from the energy exchange between ports and grid due to the higher cost of batteries (Lead acid included). Moreover the results shows that energy costs trends are tighten on a mode value, this means that the €/MWh spread is reducing thanks to a always better management of energy trades by TERNA. In this scenario the only case where the exploitation of the RES and storages of boats results convenient is the sale of RES to the grid, or the development of port grids that are able to produce and store energy for the internal consumption. This second scenario would be convenient only if state aid are given for energy self-consumption, a condition that is not present but that is likely to be adopted in the next future[8].

B. Future

The use of hydrogen gas, derived from electrolysis, as a storage medium that could provide capacity for several days or weeks. This "Power-to-Gas" approach allows for multiple use; options for the hydrogen produced include the transmission of hydrogen mixed with natural gas through the existing pipelines or use as a transport fuel. This makes the hydrogen route unique in terms of high capacity and flexibility. Moreover hydrogen technology gives the possibility to largely improve energy storage capacity of sailboats [4] permitting the exploitation of RES. The costs of the system's produced energy evaluated on the lifespan is lower or comparable with the one of Lithium Batteries although the costs of hydrogen technology does not benefit of economy of scale.

VI. Conclusions

This paper analyzed the feasibility of smart energy management of touristic harbors by means of exploiting of already installed RES generator and chemical storages (Batteries). The only present convenient solution is the use of boats RES generator all year long to sell energy to the grid covering the installation costs and the self consumption.

This solution cannot be adopted by a single boat but need harbor infrastructure to be recognized as a producer on the electricity market.

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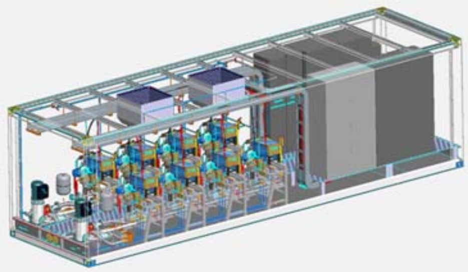
5.2 Projects related to the PhD studies

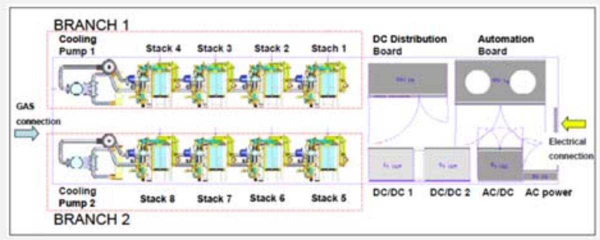
In the following a short review of the most important parallel projects developed during the PhD. studies is reported. Due to the strict collaboration with Fincantieri, restrictions are present on the dissemination of data related to the HI-SEA Joint Laboratory, that is a undergoing project. While the master thesis presented deepened the importance of alternative fuels, in particular for SSS applications. Finally, a project showing the potentiality of hydrogen technology for a passenger ship is presented.

5.2.1 From TESEO Project to HI-SEA Joint Laboratory

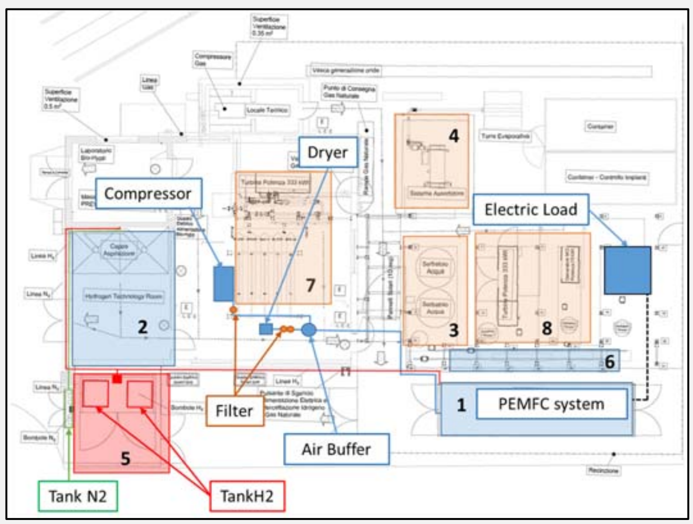
From TESEO Project to HI-SEA Joint Laboratory

The TESEO project "Tecnologie ad alta Efficienza per la Sostenibilità Energetica ed ambientale Onboard" is the Italian National cofounded project that Fincantieri developed from 2012 to 2015 in which a 30 (ft) container with a FCS of 260 kW was developed. The system was designed as a mobile laboratory to study the design and control of FCS.





At the end of the project Fincantieri decided to carry on the study integrating the FCS inside the laboratory of UNIGE in order to assess the potentiality in terms of cogeneration and trigeneration and to complete the analysis of battery hybridization of the system.



The HI-SEA Joint Laboratory has been developed in the frame of a long time signed agreement between Fincantieri S.p.A. and the University of Genoa it integrates a Hybrid PEM power generator system with the research laboratory of the Thermochemical Power Group (TPG) of the University of Genova – Savona Campus. The HI-SEA Joint Laboratory represents the first and largest effort to solve key challenges in the energy sector and to generate solutions for the low-emission ships and enhance the innovation capacity of a new business sector. The goal of the laboratory is to define the best design for a modular FC system for ship application able to guarantee the maximum life span of FC stacks without omit performance. The laboratory presents a number.

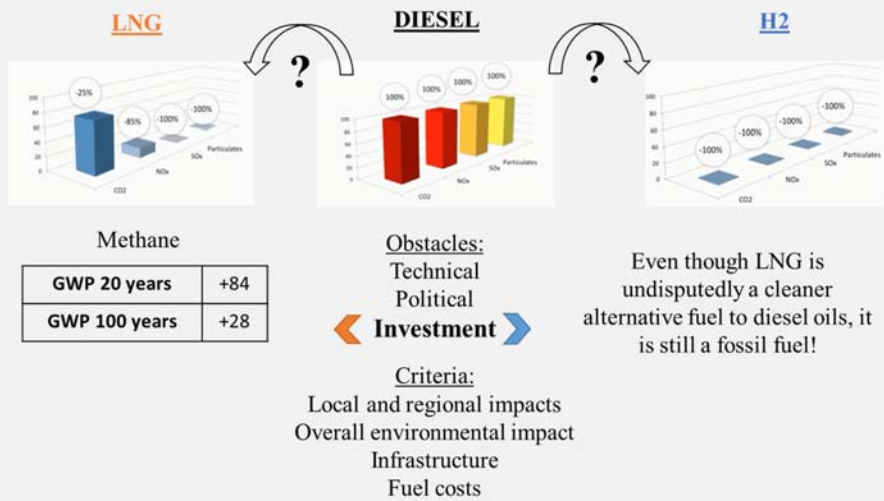
5.2.2 Alternative Low Emission Power Generation System for Short Sea Shipping

2. Alternative Low Emission Power Generation System for Short Sea Shipping

"Sustainability and energy efficiency manager in maritime transport – TrainMoS II"

Master course "TrainMoS II" – in 2013 – EU – 201012-D in the field of trans-European transport (TEN-T)

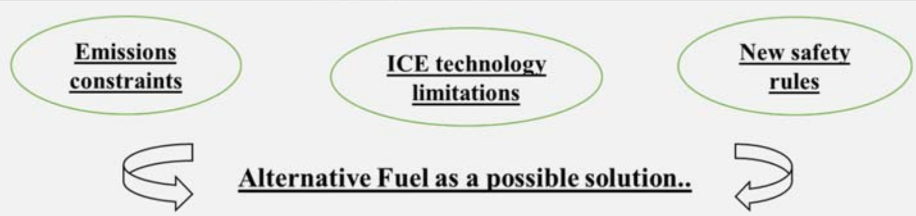
The study (9) focused on the comparison between LNG and Hydrogen as alternative fuel for ships. Both have been identified as good solution for the reduction of pollutants emissions near the coasts. But long term investment could put these solutions in competition.



For this reason an important result of the study was the identification of the Short Sea Shipping as the ideal target in order to exploit the benefit of hydrogen technologies in various sectors: Health, Energy, Transport. The combination of the advantages given by the investment by EU on SSS for the introduction of hydrogen technologies are multiplied.

The goal of this study is to assess the aptitude of SSS to implement an innovative technology onboard the ship

Some characteristics of SSS
Short distances compared to deep sea shipping → operates in limited regional area
Operates near costs and populated areas
Each vessel transports larger quantities and uses more fuel that road freight transport
Smaller ships than in deep sea shipping, decreased economies of scale for fuel consumption and t-km
Is highly subjected to political restriction



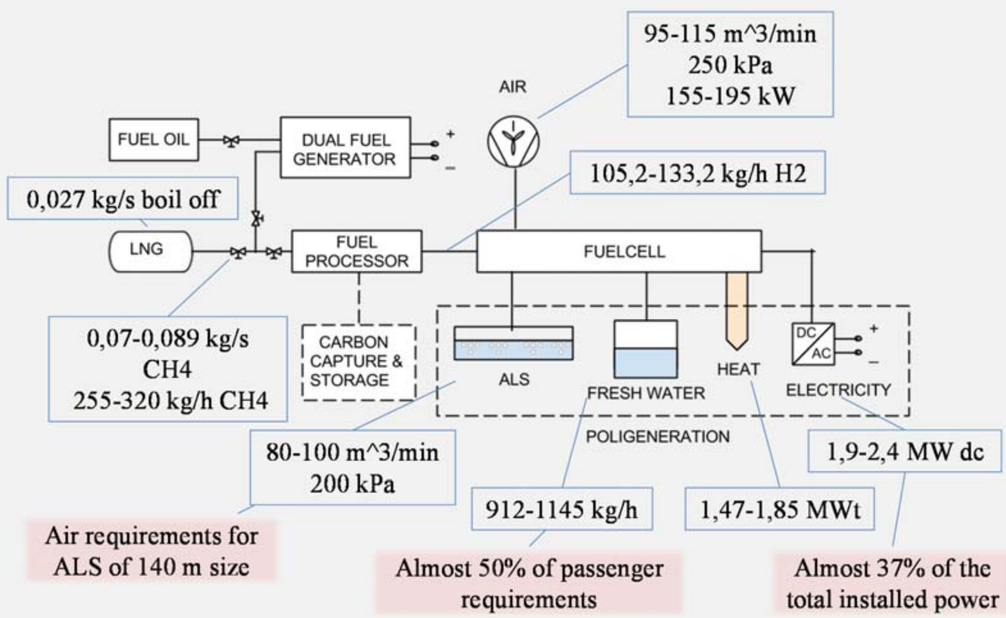
5.2.3 Fincantieri Challenge

3. Fincantieri Challenge

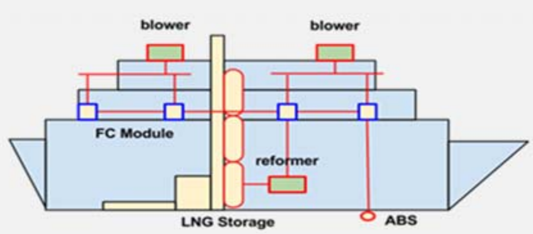
"Integrazione multifunzionale della tecnologia Fuel Cell con apparato motore diesel elettrico Dual Fuel e impianto di Air Lubrication"

"Multifunctioning integration of Fuel Cell technologies with LNG fuelled diesel-electric system and Air Lubrication system"

The idea contest was dedicated to project developed inside the University of Genova and it has been completely designed and managed by Fincantiery with CETENA. The author participate to the context together with the professors Loredana Magistri, Paola Gualeni and Enrico Ravina. The presented project won the fist stage of the context. The innovative idea consist in a poligeneration modular system able to exploit all the Fuel Cell System products and by-products: Electricity, Heat, Water and Compressed Air. The former in particular, comply in terms of flow rate and pressure with the Air Lubrification System requirements. The following figure present a simplified P&ID scheme of the system with the evaluated operative parameters for a Fincantieri "Concordia" class passenger ship.



Another peculiarity of the project idea was the installation of FCSs inside a distributed generation architecture in order to exploit cogeneration. The following figure present a schematic representation of the system design that has been later developed into the PAX Project.



5.2.4 H2Boat S.c.a.r.l

4. H2Boat S.c.a.r.l.

"Launch of the first Innovative Start-Up dedicated to the marine applications of hydrogen technology, with a particular focus on sail-boats"

H2Boat is an Italian engineering SME operating since 2015, interested in expanding business from the consultancy and experimental services in the sector of innovative energy systems, through the development of original solutions for the application of hydrogen technology in residential, power plant and particularly nautical sector. The studies conducted to the registration of a patent for the metal hydrides hydrogen storage system installed inside the keel:

Patent number 102016000046430 of the 05/05/2016, "CHIGLIA DI IMBARCAZIONE E SISTEMA DI PRODUZIONE DI ENERGIA PER IMBARCAZIONI COMPRENDENTE DETTA CHIGLIA"

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